1990

Ultimate strength of schifflerized angles.

Seshu Madhava Rao. Adluri
University of Windsor

ULTIMATE STRENGTH OF SCHIFFLERIZED ANGLES

by

SESHU MADHAVA RAO ADLURI

A Thesis
submitted to the
Faculty of Graduate Studies and Research
through the Department of
Civil and Environmental Engineering
in Partial Fulfillment of the requirements for
the Degree of Master of Applied Science at
the University of Windsor

Windsor, Ontario, Canada
June 1990

ISBN 0-315-61893-0

I hereby declare that I am the sole author of this document.

I authorize the University of Windsor to lend this document to other institutions or individuals for the purpose of scholarly research.

SESHU MADHAVA RAO ADLURI

I further authorize the University of Windsor to reproduce this document by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

SESHU MADHAVA RAO ADLURI

THE UNIVERSITY OF WINDSOR requires the signatures of all persons using or photocopying this document. Please sign below, and give address and date.

ABSTRACT

Latticed triangular-base steel towers have been used as communication structures for a long time. Since these triangular-base towers are economical, they are also being increasingly used as electrical transmission line towers. The legs of these towers generally consist of 60° equal leg angles (either 90° rolled angles bent to 60° or rolled 60° angles) which are primarily compression members.

Results of experimental investigation on eighteen equal-leg schifflerized angles (90° angles bent to 60°) under concentric axial compressive loading with hinge-hinge end conditions are presented. Five sizes of angles viz. 5x5x5/16, 4x4x1/4, $3\frac{1}{2}$x$3\frac{1}{2}$x5/16, 3x3x3/8, 3x3x1/4 in., of 300 and 400 MPa nominal yield strength with slenderness ratios varying between 50 and 95 are included in the investigation. The nominal width-thickness ratios of legs ranged between 8 and 16. The experimental failure loads are compared with loads obtained from a finite element model. The analytical problem has been solved for failure loads under geometric and material nonlinearity. A Newtonian approach with eight-node shell elements has been employed for the nonlinear solution using commercially available software "ABAQUS". Residual stress variations along the cross-section and through-the-thickness are included. All results are compared with those obtained from CAN/CSA-S37-M86, ASCE Manual No.52 and other specifications. The value of the flat width to be used in the width-thickness ratio calculations is discussed and recommendations are made.

ACKNOWLEDGEMENTS

The author wishes to express his sincere gratitude to his advisor Dr. Murty K.S. Madugula, Professor, Department of Civil and Environmental Engineering, for his guidance and patient encouragement during the development of this thesis. The author would also like to thank his co-supervisor Dr. Gerard R. Monforton, Dean, Faculty of Engineering, for his guidance and support.

Special thanks are due to Mr. Frank Kiss, technician in the Structural Engineering Laboratory and other technicians in the Central Research Shop for their assistance in conducting the experiments.

Special thanks are also due to Mr. Sreedhar Sundaram, Mr. Satya Kurada and other friends for their timely and unstinted help in typing the manuscript and plotting the curves.

The author is thankful to Mr. Donald G. Marshall, P.Eng, Vice President-Engineering, LeBlanc & Royle Telcom Inc., Oakville, Ontario, for supplying the test specimens used in the investigation free of charge.

Finally, the author wishes to acknowledge the financial support provided by the Natural Sciences and Engineering Research Council of Canada.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOTATION

The following symbols are used in the thesis :

A = *Area of cross-section*

a = *Length of un-bent portion of schifflerized angle leg*

b = *length of bent portion of schifflerized angle leg*

c = *fillet radius*

C_r = *Compressive strength*

C_w = *Warping constant*

d = *total leg width*

E = *Young's modulus*

F_{cr} = *Critical compressive stress*

F_y = *Yield stress of steel*

G = *Shear modulus*

I_{pc} = *Polar moment of inertia about centroid*

I_{ps} = *Polar moment of inertia about shear center*

J = *St. Venant's torsion constant*

K_u = *Effective length factor in u-u (major) axis*

K_v = *Effective length factor in v-v (minor) axis*

K_Φ = *Effective length factor in torsion*

$L = l$ = *Length of the column*

P_{cr} = *Critical load of column*

P_u = *Euler buckling load about u-u (major) axis*

P_v = *Euler buckling load about v-v (minor) axis*

P_Φ = *Torsional buckling load*

r = *Radius of gyration*

r_e = *Equivalent radius of gyration* for *torsional-flexural mode*

r_u = *Radius of gyration about u-u axis*

r_v = *Radius of gyration about v-v axis*

r_Φ = *Radius of gyration* for *torsional mode*

t = *Thickness of the leg of angle member*

w = *Flat width of angle member*

λ = *Column slenderness parameter*

ν = *Poisson's ratio*

ϕ = *Resistence factor*

Chapter 1
INTRODUCTION

1.1 General

The steel angle is one of the primary members used in structural engineering. It is present in almost all steel structures playing a crucial role in resisting the direct forces, moments and shears or acting as a connection piece or as a plate stiffener. Of particular importance is its near universal usage in latticed communication structures and electrical transmission towers. The main legs of these structures are primarily fabricated from steel angles which serve to transmit the gravity loads and loads due to wind, earthquake, differential wire tensions and broken wire conditions as direct forces to the foundation. The main legs are always arranged in one of the following two ways:

1. Rectangular plan with one leg at each corner of a square or a rectangle. This arrangement is generally adopted for self-supporting electrical transmission towers. The square plan makes the analysis and design relatively simple because of the ease with which the torsional and lateral loads can be resolved into in-plane forces.
2. Triangular plan with one leg member at each of the three corners. This is employed in guyed towers, self-supporting microwave towers and sometimes in electrical transmission towers. Triangular-base towers result in a significant reduction in the weight of the structure. Several

guyed and self-supporting towers of this type with heights ranging up to 600 m have been successfully designed and erected. (Figs. 1.1 and 1.2)

In the case of triangular-base towers and guyed masts, the main legs are located at the vertices of an equilateral triangle. In order to have smooth bracing connections, the included angle between the two legs of the angle members should be 60°. This is achieved by schifflerizing the hot-rolled 90° angles. Each leg is bent inwards by 15° so that the angle between the leg and the center-line of the section is 30° instead of 45° as shown in Fig. 1.3. The process involves either re-rolling or brake-pressing a 90° angle (Figs. 1.4 and 1.5). The finished member is called a schifflerized angle. This process increases the moment of inertia of the cross-section about the minor principal axis. Consequently, the member is stronger in flexural buckling and is slightly weaker in torsional-flexural buckling when compared to the regular 90° angle. The process also introduces additional residual stresses into the section which add to the existing residual stresses due to the differential cooling of hot-rolled angles. The schifflerization process, while bending the legs inward by 15° each, cannot deform the heel (or root) portion of the original regular angle because of its high rigidity. As a result, every 60° angle will have a 90° unchanged root portion of length ranging from 16 to 40 mm depending upon the leg thickness. Strengths and behaviour of these angles will be different from the regular 90° angles.

1.2 Need for Investigation

Singly-symmetric sections such as angles, tees and channels have been studied for their compressive strengths for more than a century. However, non-standard shapes, manufacturing processes and new technology do necessitate renewed investigation from time to time [SSRC 1988]. Although 60° angles are extensively used in triangular-base towers and occasionally in triangulated open web joists, no published literature is available concerning their behaviour. Various specification-writing bodies that deal with schifflerized angles have thus far depended on knowledge extrapolated from the published literature about the regular 90° angles.

The compressive strength of schifflerized angles depends on the slenderness ratio and width-thickness ratio among other things. The only reference in CAN/CSA-S37-M86 [Canadian Standards Association 1986] to width-thickness ratios for analysis is contained in clause 6.1.1, which references CAN3-S16.1-M84 [Canadian Standards Association 1984] clause 11. However S16.1 clause 11 limits the w/t ratio to $200/\sqrt{F_y}$. Many of the steel angles used as leg members in communication and transmission-line towers have width-thickness ratios in excess of $200/\sqrt{F_y}$. Therefore there is a need for studying the behaviour of members with w/t greater than $200/\sqrt{F_y}$.

There is no unanimity about the flat width to be used in the computation of width-thickness ratios. With reference to Fig. 1.3, this value can be variously taken as dimension b, (a+b), (a+b-t) and (a+b-t-c). There is therefore an urgent need to clearly define the width of the leg to be used in the width-thickness ratio calculations.

1.3 Objectives

The present study has the following objectives:

1. To conduct compression tests on different sizes of schifflerized steel angles. In general, the formulae given in various standard specifications cover flexural buckling and are applicable for many practical cases. However since the panels in towers, especially guyed towers, are relatively short, the 60° angles are more susceptible to the torsional-flexural buckling mode. The smaller major axis flexural capacity reduces its strength in torsional-flexural mode when compared to regular angle strength. Hence it was decided that the experiments should cover the flexural and torsional-flexural buckling modes.
2. Compare the experimental failure loads with values computed from various existing standard specifications.
3. Recommend the width w to be used to compute width-thickness ratios for schifflerized angles.
4. Investigate the possibility of developing a numerical model that will serve the purpose of actual testing by using finite element method to predict the ultimate strength of the schifflerized angles.
5. Using a finite element analysis, account for the effect of residual stresses on the axial compressive strength of the schifflerized angles.

Chapter 2
LITERATURE REVIEW

2.1 General

As already mentioned in section 1.2, there is no published literature on schifflerized angles. Engineers dealing with schifflerized angles depend on the general column formulae. Therefore, literature on concentrically loaded compression members, especially 90° equal leg angles, is reviewed.

2.2 Classical Column Research

Structural steel angles have been in constant use by engineers for more than 300 years. Their use as bracing members and main leg members is extensively recognized and studied. The theory of elastic buckling of concentrically loaded columns was initiated by Euler in 1744. The earliest column capacity studies were carried out in the early years of the nineteenth century by J. Robinson on non-steel columns and by E. Hodgkinson on iron columns [Todhunter 1960]. These tests showed that the well-known Euler formula does not correspond to the actual strengths. Considére conducted 32 column tests in 1889 and suggested modifications to Euler formula. In the same year, Engesser and Considére developed the theory of column buckling based on tangent modulus

$$P_T = \frac{\pi^2 E_T A}{\left(\frac{l}{r}\right)^2} \tag{2.1}$$

where E_T is the slope of the tangent to stress-strain curve at any particular stress in the nonlinear range, A is the area of cross-section and l/r is the slenderness ratio.

In 1895, Engesser modified his theory to define reduced modulus which lies in between E and E_T depending upon the shape of the cross section. In 1905, Johnson, Bryan and Turneaure [Johnson 1905] suggested the usage of Euler formula modified by a constant. In 1910, von Kārmān improved the reduced modulus theory and illustrated it by several examples.

Templin et al. [Templin 1938] studied the column buckling phenomenon under very carefully designed laboratory conditions and found that their results showed column failure at tangent modulus loads. Shanley [Shanely 1948] came up with an important explanation to the two column theories and proved that buckling starts at the tangent modulus load.

Wagner in 1929 was the first to investigate the torsional buckling of open thin walled sections. In his work, he arbitrarily assumed that the centre of rotation coincides with the shear centre which was proved to be incorrect. Ostenfeld in 1931 was the first to derive the exact solutions for torsional-flexural buckling of angle sections [Madugula and Kennedy 1985]. Bleich [Bleich 1936,1952], Lundquist and Fligg [Lundquist 1937], Vlasov [Vlasov 1940], Goodier [Goodier 1942], Timoshenko [Timoshenko 1945,1970] and Kappus, among others, have studied the theory of torsional-flexural buckling from various view points. Since then, the behaviour of angles has been the subject of several extensive studies.

Axially loaded equal-leg single angles can fail by either of the following modes:

1. Flexural buckling by bending about the asymmetric weaker principal axis.
2. Torsional-flexural buckling by simultaneous bending and twisting about the symmetric stronger principal axis.

The section buckles in one of the two modes depending on the length, cross-sectional dimensions and end conditions of the member. If the ends of the member are prevented from twisting, the column capacities can be computed as :

$$P_v = \frac{\pi^2 E (A r_v^2)}{(K_v L)^2} \tag{2.2}$$

$$P_u = \frac{\pi^2 E (A r_u^2)}{(K_u L)^2} \tag{2.3}$$

$$P_\Phi = \frac{\pi^2 E (A r_\Phi^2)}{(K_\Phi L)^2} \tag{2.4}$$

in which,

$$r_\Phi = \sqrt{\frac{1}{I_{ps}} \left(\frac{J (k_\Phi L)^2}{2\pi^2 (1 + \nu)} + C_w \right)} \tag{2.5}$$

where P_v, P_Φ etc. are as defined in the notation.

The critical torsional-flexural buckling load P_{cr} can be deduced from the quadratic equation [Timoshenko 1970] :

$$\frac{I_{pc}}{I_{ps}} P_{cr}^{2} - (P_u + P_\Phi) P_{cr} + P_u P_\Phi = 0 \tag{2.6}$$

where I_{pc} is the polar moment of inertia of the cross-section about centroid.

An examination of the above equation reveals that when the ratio $\frac{P_\Phi}{P_u}$ is relatively small, theoretical load P_{cr} is very close to P_Φ and the mode of buckling is essentially torsional. For larger values of $\frac{P_\Phi}{P_u}$ the critical load P_{cr} is close to P_u and the member buckles essentially in flexural mode. For an equal leg schifflerized angle the ratio $\frac{I_{pc}}{I_{ps}}$ is approximately 0.5. Substituting this value, the critical load can be calculated as:

$$P_{cr} = P_u + P_\Phi - \sqrt{(P_u + P_\Phi)^2 - 2 P_u P_\Phi} \tag{2.7}$$

In torsional-flexural buckling, the cross-section rotates about a point called the centre of rotation, which lies on the axis of symmetry close to the shear centre. The shear center of a 90° equal-leg angle lies at the point of intersection of the two legs. For a schifflerized angle, the shear center lies at a small distance from this point on the axis of symmetry away from the centroid.

2.3 Experimental Investigation of Angles

Equal leg hot-rolled 90 x 90 x 7 mm 90° angles have been studied under concentric loading for different slenderness ratios by Wakabayashi and Nonaka [Wakabayashi and Nonaka 1965].

Yokoo, Wakabayashi and Nonaka [Yokoo et al. 1968] have studied mild-steel equal-leg single angles under concentric loading and torsional deformations. Torsional deformations were predominant in concentrically loaded specimens. They also showed that boundary conditions for twisting do not significantly effect the failure load.

Equal leg semi-killed high strength steel angles of size 75 x 75 x 6 mm and 65 x 65 x 6 mm were tested by Ishida [Ishida 1968]. The tests showed that the load carrying capacity of mild steel angles is generally higher compared to hot-rolled high-strength steel angles which contain residual stresses.

Short [Short 1977] investigated the behaviour of single angles which buckled about the rectangular "x-x " axis and the weak " v-v " axis. The minor axis buckling loads were found to be in good agreement with ECCS recommendations [ECCS 1978].

Kennedy and Madugula [Kennedy and Madugula 1972] tested 72 angle struts with different end conditions under axial loads. All specimens were reported to have failed in the inelastic range. A procedure to estimate the realistic permissible stresses for a given angle was discussed.

Haaijer, Carskadden and Grubb [Haaijer et al. 1981] explored the feasibility of using a finite element analysis as an alternative to a physical experiment. The study included elastic behaviour.

2.4 Design Specifications

Canadian National Standard CAN/CSA-S37-M86 for towers and antenna-supporting structures deals with triangular-base towers and 60° angles. The proposed amendment No.12 dated May 8, 1990 specifies formulae similar to ASCE Manual No. 52 to include the effect of w/t ratio.

ASCE Manual No. 52 "Guide for the Design of Steel Transmission Towers " is extensively used for the design of hot-rolled angle members including 60° schifflerized sections that are used in steel transmission towers and communication structures. The formulae given for ultimate capacity are based on Euler buckling in the elastic range and on the basic strength curves of the Structural Stability Research Council in the inelastic range.

The European practice for the design of angle members is found in the " Recommendations for Angles in Lattice Towers " published by the European Convention for Constructional Steelwork [ECCS 1985]. Design procedures are included for concentrically loaded angles used in towers. The North American and the European specifications are summarized below.

2.4.1 CAN/CSA-S37-M86 proposed amendment

Maximum "w/t " ratio = 25

Effective yield stress - F'_y

i). When

$$w/t \leq 200/\sqrt{F_y}; \qquad F'_y = F_y \tag{2.8}$$

ii) When

$$200/\sqrt{F_y} < w/t \leq 380/\sqrt{F_y} \; ; F'_y = F_y\left[1.677 - 0.677\left\{\frac{\frac{w}{t}}{\frac{200}{\sqrt{F_y}}}\right\}\right] \tag{2.9}$$

iii) When

$$380/\sqrt{F_y} < w/t \leq 25 \; ; F'_y = \frac{56415}{\left(\frac{w}{t}\right)^2} \tag{2.10}$$

where, F_y is the yield stress in MPa.

Factored axial compressive resistance - C_r

$$0 < \lambda \leq 0.15, \qquad C_r = \phi A\, F'_y \tag{2.11}$$

$$0.15 < \lambda \leq 1.0, \qquad C_r = \phi A\, F'_y(1.035 - 0.202\lambda - 0.222\lambda^2) \tag{2.12}$$

$$1.0 < \lambda \leq 2.0, \qquad C_r = \phi A\, F'_y(-0.111 + 0.636\lambda^{-1} + 0.087\lambda^{-2}) \tag{2.13}$$

$$2.0 < \lambda \leq 3.6, \qquad C_r = \phi A\, F'_y(0.009 + 0.877\lambda^{-2}) \tag{2.14}$$

$$3.6 < \lambda, \qquad C_r = \phi A\, F'_y\lambda^{-2} = \phi A\left[1\,970\,\frac{000}{(KL/r)^2}\right] \tag{2.15}$$

where,

$$\lambda = \frac{KL}{r}\sqrt{\frac{F'_y}{\pi^2 E}} \tag{2.16}$$

2.4.2 ASCE Manual No. 52 (1988)

The ultimate compressive stress F_a of axially loaded compression members shall be:

$$F_a = \left[1 - \frac{1}{2}\left(\frac{KL/r}{C_c}\right)^2\right] F_y \quad when \quad KL/r \le C_c \tag{2.17}$$

$$F_a = \frac{286000}{\left(\frac{KL}{r}\right)^2} \quad when \quad KL/r \ge C_c \tag{2.18}$$

$$C_c = \pi \left(\frac{2E}{F_y}\right)^{\frac{1}{2}} \tag{2.19}$$

2.4.2.1 Maximum w/t Ratio

The ratio w/t, where w = flat width and t = thickness of leg, shall not exceed 25. If w/t exceeds $(w/t)_{\lim}$ given by

$$\left(\frac{w}{t}\right)_{\lim} = \frac{80}{\sqrt{F_y}}; \tag{2.20}$$

then the ultimate stress F_a shall be computed with F_y replaced in the above equations with F_{cr} given by

$$F_{cr} = \left[1.677 - 0.677 \frac{w/t}{(w/t)_{\lim}}\right] F_y \quad when \quad \left(\frac{w}{t}\right)_{\lim} \le \frac{w}{t} \le \frac{144}{\sqrt{F_y}} \tag{2.21}$$

$$F_{cr} = \frac{9500}{(w/t)^2} \quad when \quad \frac{w}{t} > \frac{144}{\sqrt{F_y}} \tag{2.22}$$

where F_y is the yield strength in ksi.

2.4.3 AISC - Load and Resistance Factor Design Specification

The design strength of members whose elements have width-thickness ratios less than $76/\sqrt{F_y}$ (*where F_y is in ksi*) is $\phi_c P_n$.

$$\phi_c = 0.85 \tag{2.23}$$

$$P_n = A_g F_{cr} \tag{2.24}$$

When $b/t < 76.0/\sqrt{F_y}$, (*where F_y is in ksi.*),

$$Q = 1.0 \tag{2.25}$$

When $76.0/\sqrt{F_y} < b/t < 155/\sqrt{F_y}$;

$$Q = 1.340 - 0.00447(b/t)\sqrt{F_y} \tag{2.26}$$

When $b/t \geq 155/\sqrt{F_y}$;

$$Q = 15500 \ / \ [F_y \ (b/t)^2] \tag{2.27}$$

2.4.3.1 Flexural Buckling

For $\lambda_c \leq 1.5$

$$F_{cr} = (\,0.658^{\lambda_c^2}\,)\,F_y \tag{2.28}$$

For $\lambda_c > 1.5$

$$F_{cr} = \left[\frac{0.877}{\lambda_c^2}\right] F_y \tag{2.29}$$

where,

$$\lambda_c = \frac{K\,l}{r\,\pi}\sqrt{\frac{F_y}{E}} \tag{2.30}$$

A_g = *gross area of member*

F_y = *specified yield stress, ksi*

E = *modulus of elasticity*

K = *effective length factor*

l = *unbraced length of member*

r = *governing radius of gyration about plane of buckling*

To calculate the design strength of members whose elements have width-thickness ratios greater than $76/\sqrt{F_y}$ (*where F_y is in ksi.*), λ_c and F_y are modified as $\lambda_c\ \sqrt{Q}$ and $F_y\ Q$

2.4.3.2 Torsional-Flexural Buckling

The nominal critical stress F_{cr} is determined as follows:

a. For $\lambda_e\sqrt{Q}\ \leq\ 1.5$:

$$F_{cr} = Q(0.658^{Q\lambda_e^2})F_y \tag{2.31}$$

b. For $\lambda_e\sqrt{Q}\ >\ 1.5$:

$$F_{cr} = \left[\frac{0.877}{\lambda_e^2}\right]F_y \tag{2.32}$$

where

$$\lambda_e = \sqrt{F_y / F_e} \tag{2.33}$$

F_y = *specified minimum yeild stress of steel, ksi* (2.34)

F_e = *critical torsional-flexural elastic buckling stress, ksi* (2.35)

2.4.4 BS 5950 : Part 1 : 1985

The compressive resistance C_r of an angle section is given as

$$C_r = Ap_{cr} \tag{2.36}$$

when $w/t \leq 11.5\sqrt{275/F_y}$,

p_{cr} is obtained from the Perry strut formula.

$$p_{cr} = \frac{p_E p_y}{\phi + \sqrt{\phi^2 - p_E p_y}} \tag{2.37}$$

where,

$$\phi = \frac{p_y + (\eta + 1)\, p_E}{2} \tag{2.38}$$

where, p_E is the Euler strength; p_y is the design strength; η is the Perry factor.

The Perry factor η for flexural buckling under load should be obtained from :

$$\eta = 0.001\, a\,(\lambda - \lambda_o) > 0 \tag{2.39}$$

where, a is the Robertson constant taken as 5.5 for angle struts and limiting slenderness ratio,

$$\lambda_o = 0.2\sqrt{\left(\frac{\pi^2 E}{p_y}\right)} \tag{2.40}$$

When w/t exceeds the limiting value, a reduction factor given by the lesser of

$$\frac{11}{\dfrac{a+b}{t\sqrt{\dfrac{275}{F_y}}} - 4} \tag{2.41}$$

and

$$\frac{19}{\dfrac{2(a+b)}{t\sqrt{\dfrac{275}{F_y}}} - 4} \tag{2.42}$$

is applied to the yield stress (a and b are as per Fig. 1.3).

2.4.5 ECCS Recommendations (1985)

Non-dimensional slenderness ratio $\Lambda = \lambda / (\pi\sqrt{E/F_{cr}})$ (2.43)

For equal leg rolled angles,

$$For\ \frac{b}{t} \le \left(\frac{b}{t}\right)_{lim} = 0.567\sqrt{E/F_{cr}} = 260/\sqrt{F_{cr}}, \qquad F_{cr} = F_y; \tag{2.44}$$

$$For\ \left(\frac{b}{t}\right)_{lim} < \left(\frac{b}{t}\right) < \frac{4}{3}\left(\frac{b}{t}\right)_{lim}, \quad F_{cr} = F_y\left[2 - \left(\frac{b}{t}\right)/\left(\frac{b}{t}\right)_{lim}\right]; \tag{2.45}$$

$$For\ \frac{b}{t} > \frac{4}{3}\left(\frac{b}{t}\right)_{lim}, \qquad F_{cr} = \pi^2 E/(5.1b/t)^2; \tag{2.46}$$

Values of non-dimensional column curve are given in Table 2.1.

Chapter 3
THEORETICAL ANALYSIS

3.1 Classical Theory

Basic column buckling problem has been under investigation for the last two hundred years. Classical buckling is formulated in the form of differential equations. Solutions of these equations are presented in chapter 2.

3.2 Finite Element Analysis

The finite element method can be applied to problems which cannot be effectively handled by classical theory such as nonlinear buckling coupled with irregular geometry, residual stresses etc. In the present investigation, finite element analysis is employed to study the schifflerized steel angle under various failure modes. Software package ABAQUS [ABAQUS 1989] has been used for the computer runs.

3.2.1 Discretization

For the purpose of analysis, the schifflerized angle member has been discretized into several strips of elements along the length (Figs. 3.1 and 3.2). Eight-node shell elements with 6 degrees of freedom at each node are used. The element stiffness is computed using a reduced integration scheme with four Gauss points per element.

Direct concentric loading for hinged end conditions poses a problem because the centroid of the singly symmetric angle lies outside the finite element mesh. The shell elements cannot have in-plane loading except in the form of concentrated nodal loads. Boundary conditions in the form of displacement restraint and free rotation of all nodes at each end have proved to stiffen the member. In the actual hinged end conditions, the centroid is prevented from lateral movement but is allowed to freely rotate in the two lateral directions. Any rotation at the centroid results in the movement of points on the member surface at both the ends. Restraining the member ends from translation results in increased rotational stiffness and reduces the effective length. To avoid the problem, an end plate is attached to the entire section at each end. This plate is also discretized into several elements (Fig. 3.3). The plate is made sufficiently rigid to avoid possible bending and consequent interference with the main member elements. Boundary conditions are defined only at the centroidal points on the end plates. This allows a perfect hinge condition for the member under study. The assembly consisting of the discretized member and the two end plates is loaded in the axial direction at the precomputed centroidal points.

3.2.2 Nonlinear Analysis

The problem of buckling can be solved in two ways.

1. By forming a geometric stiffness matrix of the entire structure under a fraction of the loading pattern and extracting eigenvalues and mode shapes. This is useful only when the structure remains elastic until buckling.

2. By conducting a nonlinear analysis. In this case, buckling is indicated by excessive deformations and consequent reduction in load carrying capacity.

In the present study buckling loads are estimated using nonlinear analysis. This method allows for both material and geometric nonlinearities in the structure.

Several solution techniques are available to tackle such problems [Powell and Simons 1981; Bergan et al. 1978; Crisfield 1986; Matthies and Strang 1979]. Of these, Newtonian strategies are widely known. The nonlinear solution is obtained by iteratively solving a series of linear problems. At any displacement configuration, let $\{u\}$ be the vector of nodal displacements; $\{F_e\}$ the vector of external nodal loads; $\{F_i\}$ the vector of internal resisting forces; $[K]$ the tangent stiffness at the present displacement state. The unbalanced portion of the nodal forces is given by

$$\{F_u\} = \{F_e\} + \{F_i\} \tag{3.1}$$

$\{F_u\}$ represents the error in the present solution as represented by the displacement state $\{u\}$.

The iterative technique for Newtonian type solutions is as follows:

$$\{F_u^{\,j}\} = \{F_e\} - \{F_i^{\,j}\} \tag{3.2}$$

$$\Delta r^j = [K^j]^{-1}\ F_u^{\,j} \tag{3.3}$$

$$r^{j+1} = r^j + \Delta r^j \tag{3.4}$$

$$F_i^{\,j+1} = \mathit{function\ \ of}\ r^{j+1} \tag{3.5}$$

The structure loading is divided into several increments and at each increment, the nonlinear equations are solved using either Newton's method or variations of it which are referred to as quasi-Newtonian techniques. These involve various types of automated control of load increment, handling of snap-through buckling, etc.

3.2.3 Determination of Failure Load by Finite Element Method

The schifflerized angle finite element model is used to perform a nonlinear static analysis under concentric loading. The load at which the member starts to have a decrease in axial load capacity or becomes geometrically unstable is considered as the buckling load. The finite element model cannot have such failure under a perfectly concentric load alone. Under a perfectly concentric load, the only failure possible is that when the section becomes entirely plastic and material instability sets in. In the real specimen the load is invariably eccentric and at the buckling load, this eccentricity initiates large deformations. In the finite element model this can be simulated by creating an artificial eccentricity for the applied load in the form of an initial out-of-straightness. This is generally done by assuming that the initial geometry is in the form of a half sine-wave with central deviation equal to 1/500 to 1/2000 of the member length. In the present study, this is achieved by placing small trigger loads at strategic points to create the desired buckling mode. For flexural buckling, a small load of about 1/1000 of the expected failure load is applied at the mid-height along the major axis. For torsional-flexural buckling mode, a trigger load is applied at the heel of the angle at mid-height in the minor axis direction. This creates a load in the minor axis direction and a torque about the centroid which starts the torsional-flexural mode. The same effect can be achieved by applying end moments at the centroid or two loads at the toes of the legs at mid-height. However, care must be taken to avoid mixing up of the two modes, as the moments in flexural mode tend to shift the load from centroid towards or away from the shear centre which in turn alters the torsional-flexural load capacity considerably.

3.2.4 Residual Stresses

Hot rolled angles develop residual stresses because of the differential cooling process. These residual stresses affect the ultimate load carrying capacity of the member by initiating yielding of some parts of the member before the other parts. Residual stress pattern for 90° angles has been studied by a number of researchers. It is currently an accepted practice to adopt the recommendations made by ECCS [ECCS 1985] as shown in Fig. 3.4. The stresses given in Fig. 3.4 are in the longitudinal direction. In the present investigation, a residual stress distribution similar to Fig. 3.4 is used for the schifflerized angle. In addition, the schifflerization process involves permanent bending of the legs of the angle. This is achieved only by yielding of the section around the line of bending. Release of the section after schifflerization induces residual stresses in the leg which vary through-the-thickness of the leg in the transverse direction (Fig. 3.5). These stresses do not directly affect the axial buckling load. However, the transverse residual stresses introduce longitudinal stresses because of the Poisson's effect. Hence, the residual stress distribution in the longitudinal direction for schifflerized angle is a superimposition of the variation due to hot-rolling as given by ECCS [ECCS 1985] and the variation due to schifflerization process. Numerical simulation of residual stresses with the shell element model is achieved by defining an initial stress pattern at each of the integration points through a user subroutine. For the purpose of 'through-the-thickness' variation of residual stress, the shell element thickness is divided into twelve parts and the residual stress is defined at each of the resulting thirteen points. The total residual stress which is the sum of longitudinal 'hot-rolling' stress and the longitudinal 'schifflerization stress' at each of the thirteen points is taken as the starting stress which is added to the stress due to external loading in the first load increment. In effect, the residual stresses are treated as results of an earlier linear elastic load case.

Typical deformed shapes of schifflerized angles under nonlinear analysis are shown in Figs. 3.6 to 3.10.

Typical outputs from ABAQUS for failure load are given in the Appendices D, E and F.

Chapter 4
EXPERIMENTAL INVESTIGATION

4.1 General

Tests were conducted on five different sizes of schifflerized angles with 5x5x5/16, 4x4x1/4, 3.5x3.5x5/16, 3x3x3/8 and 3x3x1/4 in. nominal dimensions. These sections are generally used in panels with heights ranging between 1.2 and 2.0 m. To represent a typical field usage, column slenderness ratios are chosen to range between 50 and 100.

All members are tested under pinned end conditions so that the critical section for buckling will be at the mid-height. This reduces the effect of end plate assembly on the critical section to a minimum [SSRC 1988].

4.2 End Connections

Hinged end conditions are created using an assembly of plates and knife-edges. Each end is made up of an assembly consisting of three plates separated by two knife-edges (Fig. 4.1). The middle plate contains straight grooves (angle of cut 120°), one at the top and one at the bottom. These grooves are made perpendicular to each other in order to facilitate free rotation in two orthogonal directions. The top and bottom plates contain grooves (angle of cut 90°) on one side, facing the middle. The top and bottom plate grooves hold the knife-edges firmly while the knife-edges are free to rotate on the middle plate.

The knife-edge is made of a 30 mm square bar placed on edge. One edge fits completely into the top (or bottom) plate groove while the diagonally opposite edge fits loosely into the groove on the middle plate. One such assembly is attached to a bracket from a loading frame while the other assembly is placed on top of the loading cell. The angle specimen is placed in between the two end-plate assemblies. The effective length of the member is the distance between the free rotating edge of bottom knife-edge to the free rotating edge of the corresponding parallel knife-edge at the top. The top and bottom assembly axes are arranged perpendicular to each other in order to achieve the same effective length in both major and minor axes. To facilitate the alignment of the specimen and to prevent the ends of the specimen from slipping or kicking out during the loading, the plates directly bearing the member are provided with movable blocking plates (Fig. 4.2). Once the alignment of the column is fixed, these blocking plates can be firmly screwed to the bearing plates. This holds the member firmly in place and prevents accidental kicking out.

4.3 Fabrication of Test Specimens

Three angle members per size tested are cut from the same stock to minimize variations and imperfections. The length of each member was approximately 1.5 m. Both ends of each specimen are milled to be perfectly parallel to each other and perpendicular to the longitudinal axis. The ends are supported on top and bottom plate assemblies by simple bearing. The ends are prevented from lateral movement by movable blocks.

4.4 Alignment of Test Specimen

The most critical aspect of the column testing under concentric loading is its alignment. The member should be placed in the loading arrangement in such a way that the longitudinal axis and the line of action of the load coincide. Alignment eccentricity of as low as 5% of the cross-sectional dimension can cause considerable reduction in failure load. Alignment based on calculated values of centroid marked on the bearing surfaces can give errors because of the possible shift of knife-edges, load cell, jack etc., while setting up the specimen. Alignment based on theodolite readings was not found to be very satisfactory. To avoid such difficulty, the final alignment of specimen is achieved by the use of electrical resistance strain gauges. The specimen surface is carefully prepared using air operated grinders. Several 5 mm electrical strain gauges (steel type : SHOWA-N11-FA-5-120-11) are installed on the prepared surface of the specimen (Fig. 4.3). The wide scatter in the location of the these strain gauges enables the detection of any strains due to bending of the member under eccentric loading. The strain gauges are connected to standard resistance bridges which give readings in microstrains. The member is loaded initially to about 20% of the expected failure load and all the strains are recorded. Differences in the strains indicate the possible bending due to eccentricity at top and or bottom. For a perfectly aligned specimen, strain in all gauges should be the same. If they are different from each other, the member is unloaded and is readjusted to reduce eccentricity. The process is continued to achieve the best possible alignment (for a typical test specimen, the total number of such adjustments can vary from 20 to 80 and can take 2 to 6 hours).

4.5 Testing

A 900 kN hydraulic jack was used to apply compressive loading. This is connected to a pump which gives adequate control of the loading process. A 900 kN universal flat load cell is placed on the jack and is connected to a pre-calibrated digital load indicator.

The load was applied in steady increments usually at about 5% to 10% of expected failure load. The complete setup is shown in Figs. 4.3 to 4.6 . These show the bottom support, the flat jack, pump, flat load cell, bottom and top end-plate assemblies, load and strain indicators. A typical test took an average of 6 hours to complete. Figs. 4.7a to 4.13 show typical test specimens in their buckled state.

In concentric column testing, the strain gauge readings and load-deflection data are used to monitor the alignment of the test specimens and to get an idea of the approach of failure load. In the present investigation, the deflections and rotation at mid-height were measured using mechanical dial gauges having a travel of 75 mm and a 0.01 mm least reading.

Typical load-deflection data and strain gauge readings are shown in Appendix A.

4.6 Tension Test on Standard Coupons

Tension tests were conducted on standard size coupons from the same stock as that of test specimens. The strain is measured on a 50 mm gauge length by a metal testing averaging type breakaway extensometer. The results are plotted on a flat bed X-Y electronic recorder. Fig. 4.14 shows a typical tensile coupon being tested in a 600 kN Tinius Olsen Universal Testing Machine. Two coupons are tested for each section size (Figs. 4.15a to 4.15c). Average values of yield stresses are used in computations.

4.7 Stub Column Testing

For the purpose of determining the magnitude of residual stresses, the member is normally sliced into thin strips. This relieves the initial strain and thus changes the length of the strip. The difference in these lengths gives a measure of residual stresses. The effect of through-the-thickness variation of the residual stresses can be found by drilling holes on the surface of the test specimen to the desired depth and observing the change in strain in an electrical resistance gauge. However, in the present study the overall magnitude of the residual stresses in the section is sought to be measured using stub column test.

The stub column test gives a measure of the total effect of residual stresses on the column strength. For this purpose, a piece of the test section 330 mm long was cold sawed from the same stock as those of the test specimens. The length was chosen as per SSRC guidelines. The ends of the stub column thus obtained were milled plane and perpendicular to the longitudinal axis. The properties were measured and recorded. The stub column was then tested in a universal testing machine to obtain the stress-strain relationship (Fig. 4.16).

Chapter 5
DISCUSSION OF RESULTS

5.1 General

This chapter describes the results of experimental investigation and theoretical analysis. The geometric and mechanical properties of the test specimens are first determined. The data thus obtained is used for finite element analysis and to calculate loads as per various standard specifications. Both quantitative and qualitative observations made during the course of the entire investigation are discussed. The objective of this discussion is to interpret and understand the results and to focus on their implications.

5.2 Properties

5.2.1 Geometric Properties

Geometric properties of angles have been calculated based on the accepted practice in North America. The cross-section is idealized into segments of four rectangles by ignoring toe and fillet radii (Fig. 1.3) and the following formulae are derived for geometric properties.

$$A = \text{area of cross-section} = 2t\,(a+b-t/2) \tag{5.1}$$

$$d = \text{leg width} = a+b \tag{5.2}$$

$$u_c = \frac{2(a-t/2)^2 + 4b(a-t/2) + \sqrt{6}b^2}{4\sqrt{2}\,(a+b-t/2)} \tag{5.3}$$

$$I_u = 2\,(I_{u1} + I_{u2}) \tag{5.4}$$

where,

$$I_{u1} = \frac{3bt^3}{16} + \frac{b^3 t}{48} + bt\left(\frac{b}{4} + \frac{(a - t/2)}{\sqrt{2}}\right)^2 \tag{5.5}$$

and

$$I_{u2} = \frac{(a - t/2)t^3}{24} + \frac{t(a - t/2)^3}{6} \tag{5.6}$$

$$I_v = 2\,(I_{v1} + I_{v2}) - Au_c^2 \tag{5.7}$$

where,

$$I_{v1} = \frac{bt^3}{48} + \frac{3b^3 t}{48} + bt\left(\frac{(a - t/2)}{\sqrt{2}} + \sqrt{3}\frac{b}{4}\right)^2 \tag{5.8}$$

and

$$I_{v2} = \frac{(a - t/2)t^3}{24} + \frac{t(a - t/2)^3}{6} \tag{5.9}$$

$$I_{pc} = I_u + I_v \tag{5.10}$$

$$I_{ps} = I_{pc} + Au_c^2 \tag{5.11}$$

$$r_u = \sqrt{\frac{I_u}{A}} \tag{5.12}$$

$$r_v = \sqrt{\frac{I_v}{A}} \tag{5.13}$$

$$r_{ps} = \sqrt{\frac{I_{ps}}{A}} \tag{5.14}$$

$$J = \frac{2}{3}\,(a + b - t/2)\,t^3 \tag{5.15}$$

$$R = \text{shape factor} = 1 - \frac{u_c^2}{r_{ps}^2} \tag{5.16}$$

$$r_e = \frac{1}{2R}\left(r_u^2 + r_\Phi^2 - \sqrt{(r_u^2 + r_\Phi^2)^2 - 4Rr_u^2 r_\Phi^2}\right) \tag{5.17}$$

where all the symbols are explained in the notation.

All cross-sectional properties are computed using the computer program given in Appendix B. (The geometric properties are obtained by converting the imperial dimensions into SI system). The actual cross-sectional dimensions d and t are measured at five locations along the length on each leg and their average is adopted for further computations. The unschifflerized length 'a' of each section is taken as per the current practice in industry. The actual and nominal properties used in computing member strengths are listed in Tables 5.1a to 5.1f. An examination of these properties reveals that the member areas for specimens with nominal sizes 5x5x5/16, 4x4x1/4 and 3x3x1/4 in. are lower by up to 2.5% when compared to the nominal areas. For members of sizes 3.5x3.5x5/16 and 3x3x3/8 in., the areas are higher by up to 2% when compared to the nominal areas. The moments of inertia for sizes 5x5x5/16 and 4x4x1/4 in. are lower by up to 5% when compared to the moments of inertia based on nominal dimensions. The corresponding values for the remaining specimens are higher by up to 5% when compared to their nominal values.

5.2.2 Mechanical Properties

Results of tests on tensile coupons (as per ASTM standards) were used to determine the mechanical properties of the material being tested. One coupon per leg per section size was selected. The load-strain curves for each of these coupons are presented in Figs. 4.15a to 4.15c. The actual yield stress calculated as the average of the yield stress from both the legs of the section is used in all computations. The actual yield stresses are found to be 11 to 23% higher than the corresponding nominal values. The value of Young's modulus is taken as 200 000 MPa as per established practice. Table 5.2 lists the mechanical properties of the tensile coupons.

5.3 Theoretical Computations

5.3.1 Classical Approach

Theoretical investigation involves classical column buckling theory. If the member has a nonlinear stress-strain relationship, the failure loads can be estimated using the tangent modulus E_T instead of E for flexural buckling. An approximate shear modulus which is generally taken as G_T [*where*, $G_T = E_T / 2(1 + \nu)$] can be used for torsional-flexural buckling. However, if the member enters the plastic stage, the classical theory fails to give accurate results. In addition, the classical theory cannot effectively handle the residual stress distributions. All specimens used in the investigation fall in the intermediate range of slenderness. All test columns entered plastic stage. The classical elastic theoretical loads are computed using the computer program given in Appendix C. Since all the specimens failed by inelastic buckling, the results obtained from the classical elastic theory are not presented for discussion.

5.3.2 Finite Element Analysis

The finite element analysis as described in Chapter 3 has been carried out for each of the test specimens using the actual dimensions. Elastic range is defined using nominal value for Young's modulus (E=200 000 MPa). An elastic-perfectly plastic model is used for material nonlinear analysis.

In order to verify the suitability of the present model of finite element analysis for the problem, a series of numerical tests were carried out using commercially available software "ABAQUS" (as mentioned in Ch.3).

5.3.2.1 Convergence Test for Flexural Buckling

To test the convergence properties of the finite element mesh, a sample problem is analyzed for purely elastic case.

A 150x150x10 mm 90° angle specimen of length 2500 mm has been selected for flexural buckling mode. The member was discretized using eight-node shell elements and analyzed for geometric nonlinear failure load under perfectly elastic conditions. The initial crookedness is introduced by a small concentric load which is about 1/500 of the expected failure loa applied in the u-u direction at mid-height (the same method is followed in the actual analysis of the test specimen). The mesh has converged close to the theoretical buckling load as predicted by classical theory (Fig. 5.1).

5.3.2.2 Convergence Test for Torsional-Flexural Buckling

A 150x150x10 mm 90° angle specimen of length 1525 mm has been selected for torsional-flexural buckling mode. The angle is discretized in the same manner as in the case of flexural buckling mode. The problem is analyzed under initial crookedness to create torsional-flexural buckling. Over twenty different ways of creating the torsional buckling mode have been employed and the failure loads were estimated under perfectly elastic conditions. All the different ways of creating the torsional failure have given the results within a close range. Of these models, the crookedness introduced by a mid-height concentrated load at the toe of each leg forming a twisting couple and a resultant load in the minor axis direction has been found to yield results closest to the theoretical load. This mode of initial out-of-straightness has been adopted for further mesh refinement. The mesh has again converged quickly to the estimated thoretical load (Fig. 5.2).

The same kind of analysis has been carried out for elastic-perfectly plastic model for both flexural and torsional-flexural modes of failure. The rate of convergence of the mesh has been observed and the optimal mesh size has been selected as one with 5 segments along the length with 8 elements per segment.

5.3.2.3 Effect of Thickness of End Plates

To test the effect of the end plate rigidity on failure load, a perfectly elastic problem has been analyzed with varying thicknesses of end plates. It is found that an end plate thickness that is less than five times the leg thickness of the angle member has an effect on the failure load. For such thicknesses the end plate tries to bend along with the member legs and the resulting failure load does not represent the true buckling load.

5.3.2.4 Effect of the End Plate Size

To test the effect of the end plate size on the failure load, an elastic model has been analyzed with various shapes of the end plate having thickness equal to 16 times the leg thickness. It is found that any reasonable shape of the plate that connects the centroid of the section with all the nodes of the leg elements gives satisfactory results.

5.3.2.5 Effect of End Plate Assemblies

To test the effect of the end connections used in actual testing setup, the end plate-knife-edge assembly (Fig. 4.1) has been discretized using shell elements. For such assembly of plates, the finite element model assumes the nodes to be in the mid-surface of each plate. In the physical setup, these surfaces are not in actual contact with each other but are separated by the thicknesses of the plates. The problem of thickness offset of the elements because of the "plate to knife-edge to plate " connection has been studied in two ways:

1. By giving actual thickness to each plate and average thickness to the knife-edge along their centre lines and connecting them with multi-point constraints to transfer displacements and rotations.
2. By employing very rigid shell elements with large thickness to close the gap between the centerlines of plates and the edges of knife-edges.

In both the cases, the finite element modelling of the end plate assembly did not show appreciable difference in failure load from the load obtained using a single plate at each end of the full effective length of the member.

5.3.2.6 Effect of Variation of Yield Stress

Effect of the variation of the material yield stress on the failure load has been studied using a 75x75x10 mm 60° angle of length 1650 mm. As expected, the results show a nonlinear relationship between yield stress and the failure load (Fig. 5.3).

5.3.2.7 Effect of Variation of Young's Modulus

Effect of variation of Young's modulus on the failure load of an elastic-plastic column, studied using the same model as above has revealed that the finite element failure load for a constant yield stress does not vary linearly with Young's modulus. The failure load (Fig. 5.4) varies in a slightly nonlinear manner with increase in the value of E. But for practical purposes, the variation from linearity is negligibly small.

5.3.2.8 Effect of Location of Load Point

Effect of the location of the point of application of the axial load has been extensively studied using the finite element model. The results showed that an eccentricity of even five percent of the leg width can considerably reduce the flexural buckling capacity of the column. The results also confirmed the prediction of classical theory, that the member will have higher torsional-flexural buckling capacity if the point of application of axial load moves towards the centre of rotation [Timoshenko and Gere 1970].

5.3.2.9 Effect of Slenderness Ratio

Effect of the slenderness ratio on the failure load has been studied using a 75x75x10 mm 60° angle (nominal yield 300 MPa). The resulting relationship between load and slenderness ratio has followed the established predictions (Fig. 5.5). In the elastic range, the curve follows Euler equation and in the inelastic range, the curve shows a trend similar to that of the ECCS curves.

5.3.2.10 Effect of Residual Stresses

Effect of the residual stresses on the angle member has been studied by adopting a slightly modified version of the ECCS recommendations. All the maximum ordinates of the standard ECCS residual stress curve are taken to be equal in magnitude disregarding the small variation in the original curve. A 75x75x10 mm column of length 1020 mm has been studied with varying magnitudes of the residual stress ordinates. The influence of the maximum residual stress ordinate as percentage of yield stress on the failure load of a typical member is presented in Fig. 5.6. The rate of reduction of failure load decreases with increase in the percentage of residual stress.

The effect of through-the-thickness variation of the residual stresses on failure load has been computed and has been found to be less than 2% to 4% of the load without such variation.

The effect of the tranverse residual stresses due to schifflerization process has been studied by defining initial stresses in the transverse direction at thirteen points along the cross-section thickness near the line of bend of each leg. It is found that these stresses do not effect the axial load carrying capacity of the member.

5.4 Experimental Investigation

5.4.1 Member Capacities

This section focuses on the ultimate load capacity and the failure modes of test specimens.

Of the five different sizes of members tested, sizes 5x5x5/16 in. and 4x4x1/4 in. were analyzed beforehand and were choosen with the appropriate length so as to cause failure in torsional-flexural mode. All six specimens tested for these sizes failed in the torsional-flexural mode as expected. It is interesting to see in the published literature, a long drawn-out debate about the legitimacy of calling torsional-flexural buckling as local plate failure. CAN3-S 16.1-M84 [Canadian Standards Association 1984] specifies a limiting (w/t) ratio of $200/\sqrt{F_y}$. This limit is generally taken to represent the susceptibility of the leg plate to local failure. Angles in both the sizes 5x5x5/16 in. and 4x4x1/4 in. have (w/t) ratio in excess of this limit. In the present investigation, the failure process has been closely monitered in order to determine the nature of buckling. Initial load increments were kept at about 1/20 of the expected failure load. As the load approached the failure limit, the load increments were reduced to about 1/50 of the buckling load. In all the six test specimens in this category, the failure occurred suddenly and without any delay between local plate failure and overall torsional-flexural buckling. But it may be of interest to note that from the angle of observation during the present investigation, the failure seemed to have occurred first in local plate buckling mode, immediately followed by failure in overall torsional-flexural buckling mode. The failure is always accompanied by a loud noise. None of the failures were purely in plate buckling mode. No member failed by local failure of plates in which legs buckled in opposite directions. It may also be of interest to note that there was an appreciable amount of flexural bending about the minor axis in all the torsional-flexural buckling modes. However, the minor axis flexural buckling did not seem to be affecting the magnitude of failure load.

All the members in this category have tried to twist the end plate assembly at the time of buckling. In the present setup , the top plate assembly has been firmly fixed to the top bracket which is attached to the loading frame. The bottom plate assembly however, has been placed on top of the flat load cell, which in turn rests on top of the flat jack. There is no special arrangement at the bottom to prevent twisting of the member except the high static frictional force developed under the buckling load. Members of size 4x4x1/4 in. have failed while attempting to twist the bottom plate assembly on top of the flat jack. The final failure was accompanied by twisting of the bottom end of the member. The first two specimens of this category have failed in the bottom 1/5 portion of the member height (Figs. 4.7a to 4.7c). When specimen S4-1/4-3 has been tested under a temporary arrangement to resist bottom plate rotation, the member could not manage to twist the support assembly, but failed in the top 1/5 portion of the member height (Fig. 4.8). The failure load of this specimen was recorded to be approximately 10% higher than the other two specimens of the same size and length. The result seemed to contradict the finding of Yakoo et al. that end conditions do not effect the failure load in torsional-flexural buckling mode. However it should be noted that the present observation is made on the basis of only a few test specimens and no attempt has been made to measure the amount of partial restraint offered by the static friction between the end plate assembly and the load cell. The real increase in failure load might have been due to some partial restraint to the end rotation of the member about major axis provided by the temporary arrangement.

Members of size 5x5x5/16 in. failed in torsional-flexural mode at mid-height. In all cases, some twisting of the bottom assembly was observed (Figs. 4.9a and 4.9b).

Specimens of nominal size 3x3x1/4 in. have their (w/t) ratio just bordering on the specified limit. All three members of this size failed by flexural buckling. But it is of interest to note that all three specimens of this size failed by buckling about both minor and major axes (Figs. 4.10a and 4.10b). No appreciable twisting has been observed. The reason for this could be the fact that flexural and equivalent torsional-flexural radii of gyration for these members do not differ greatly. The elastic-plastic flexural buckling capacities of these members about minor and major axes computed using finite element analysis are very close to each other. Another reason could be that after buckling, the member alignment changes and additional axial compression applied can easily result in bending about the major axis. To avoid any possible twisting and consequent failure in torsion, the bottom assembly for S3-1/4-2 and S3-1/4-3 was provided with additional restraint against twisting (as in the case of S4-1/4-3). The arrangement seems to have slightly increased the failure load. When specimen S3-1/4-1 was tested without any additional arrangement for bottom restraint, the failure load came out to be less than the corresponding loads of the other two specimens of the same category.

Size 3.5x3.5x5/16 in. specimens have (w/t) ratio further below the specified limit when compared to size 3x3x1/4 in. specimens. All three specimens of this size have failed by flexural buckling about minor axis (Figs. 4.11 and 4.12). No appreciable twisting or deflecticn about the major axis has been recorded. The member load increments were reduced to about 1/50 of the expected load in the final quarter of loading. It was observed that the failure is slow and steady. Once the member reached its ultimate capacity, at constant load the deflections of the member at mid-height have increased slowly and the members took almost 10 seconds to fail completely by flexural buckling.

Size 3x3x3/8 in. specimens have (w/t) ratio below the specified limit. All specimens of this size have failed by flexural buckling about minor axis and no appreciable twisting or deflection about major axis have been recorded (Fig. 4.13). The final mid-height deflection was less than half of what could be expected from the corressponding deflections of other sizes. After buckling, the test specimens of this size sustained loads that are considerably higher than the corresponding loads for other sizes. This may be due to the fact that members of this size have very high yield strength (475 MPa) and lower (w/t) ratios.

Table 5.3 lists the failure loads for all the specimens along with their slendemess ratios.

5.4.2 Loading and End-Plate Assembly

Loading of the members has been carried out via a flat jack which was operated by a hand pump. Although the SSRC guidelines for column testing recommend a constant rate of loading by a mechanical pump, a hand operated pump has been found to be satisfactory for the purpose of the present investigation. The hand pump not only gave good control over the load increments but also allowed easy recording of observations. The loads were monitored by a digital indicator and the reading was accurate to within 0.5% of failure load. The load cell was calibrated twice during the testing process and no change in the calibration curves was observed.

The end plate assembly described in Chapter 4 was found to be adequate for flexural buckling. The knife-edges did not pose any restraint to rotation of the plates about the minor or major axis. But, as already mentioned, the bottom plate assembly could not provide complete fixity against twisting of the member (more sophisticated experimental setups can be designed with several kinds of end fixtures. For example, the setup used by Wilhoite et al. [Wilhoite et al. 1984] uses Cardan's joints with an automated adjusting mechanism).

The loading frame has been found to be adequate for the range of loads experienced in the present investigation.

The movable blocks (Fig. 4.2) used to provide protection against accidental 'kicking-out' of the member ends have proved to be necessary in torsional-flexural buckling. All the members that failed in that mode have tried to twist the bottom plate assembly by transfering lateral forces through the screws used to hold the blocks firmly to the top of the top plate of bottom assembly. Specimen S4-1/4-3 has exerted sufficient lateral thrust so as to cause partial shearing of one such screw.

5.4.3 Alignment and Measurements

The member alignment has been achieved by attaching several electrical strain gauges to the surface of the member at different locations. The criterion for concentric loading has been taken as that alignment which produces strain gauge readings with least deviation. SSRC recommendations indicate that a total of 18 strain gauges can be placed on the surface of the angle (five each at top, bottom and mid-height). Attaching these strain gauges is a costly and tedious process. In order to see the effect of the number of strain gauges on the alignment of the angle, different combinations of strain gauge locations have been experimented with. Eight specimens have been experimented with with zero, 3, 5, 7, 9, and 11 strain gauges. The first two test specimens have been discarded because of poor alignment. It is observed that the minimum number of strain gauges required for alignment is five. The five strain gauges are placed at (Fig. 4.4),

1. heel of the top end
2. heel at mid-height
3. toe of one of the legs at mid-height
4. toe of the other leg at mid-height
5. toe of one of the legs at bottom end.

These five strain gauges monitor eccentricities at the middle and indicate the differential eccentricities at both the ends. However alignment with the use of 9 strain gauges (3 at each section) is found to be easier and faster although the final result is not appreciably different form the result obtained from attaching five gauges.

The strain gauge readings were recorded at each load increment till the final phase of loading before buckling. The strains after buckling of the specimens for the mid-height gauges were observed to have readings several times their pre-buckling readings. The readings at the ends of the member also showed a good jump, although the end sections are not expected to have yielded. The load carried by the member after buckling was almost constant under increasing axial deflection. This may be due to the fact that with increase in axial deflection after buckling, the member ends rotate and the corresponding rotation of the end plates creates a 'follower' type axial load that rotates with the member ends.

Deflections at mid-height have been recorded with dial gauges. Two dial gauges have been used to measure mid-height deflection along the major axis. Two more dial gauges recorded deflection of the two legs at the toe. The average of the first two gauges was used as deflection along u-u axis. Average of the second set is used as v-v deflection. Difference of the second set of readings served to indicate the twist of the member at mid-height. None of the members has shown appreciable deflection or rotation before buckling.

Upon unloading, at least half of the deflection along the major axis has recovered for the members that failed in flexural buckling. No appreciable recovery was observed for torsional-flexural buckling.

Stub-column tests as described in Ch.4 were carried out for test specimens. However, due to the limitation of the capacity of Universal Testing Machine, only one section size (nominal 3x3x1/4 in.) could be fully tested to failure (Fig. 4.16). The results indicate that the magnitude of maximum residual stress on the section is almost 50% of the yield stress. However, no conclusions can be drawn from this single test.

5.4.4 Comparison of Experimental and Finite Element Loads

Table 5.4 lists the member failure loads obtained from experimental investigation and finite element anaysis. Except for specimens S4-1/4-3, S3-1/4-2 and S3-1/4-3, all the specimens have FEM results within 5 to 10% of the experimental loads. For those three specimens, it may be noted that the bottom plate assembly has been slightly modified to prevent twisting of the assembly. This arrangement, as already pointed out, has resulted in increased experimental loads. The finite element analysis predicts loads within 5% of the theoretical failure loads for elastic buckling. Assuming that the margin of error due to finite element analysis in inelastic buckling is the same as in the case of elastic buckling, the computed loads are very close to the experimental loads. In almost all cases, the predicted loads are slightly less than or just above the experimental loads. From the results obtained, it appears that the finite element analysis with all the underlying assumptions, did give reasonably good results when compared with the experimentally obtained failure loads.

5.5 Comparison of Experimental Loads with Specifications

5.5.1 General

This section focuses on the loads calculated as per various standard specifications and recommendations and their comparison with the experimentally obtained values. As mentioned in Chapter 1, the column capacity is influenced by the w/t ratio. For sections with w/t ratio more than a specified maximum, the applicable critical stress is derated by a reduction factor. For 60° schifflerized angles, the value of w can be variously taken as (b), (a+b-t-c), (a+b-t) or (a+b) [refer Fig. 1.3]. All these different values of w are used in the present discussion to predict member capacity as per different standard specifications. Some of the specifications refer to a resistance factor ϕ. The computed resistances are to be derated using this factor. But in the case of present disscussion, the value should be taken as 1.0 because of the usage of actual test specimens. Therefore, all the column capacities are computed using the actual properties, yield stresses and a resistance factor of 1.0. However, in the design office practice, it is very rare that individual members are tested to find their resistance. In any typical design situation, the nominal values are used to find member capacities. In view of this, all the computations are repeated using nominal properties (dimensions and yield stress) and applicable resistance factors. All computations are performed using the computer program given in Appendix C.

Specimens of nominal size 5x5x5/16 in. and 4x4x1/4 in. have their w/t ratios above the specified limits for all the different possible values of w. These specimens have different load capacities for each value of w. Specimens of nominal size 3.5x3.5x5/16 in. and 3x3x1/4 in. have their w/t ratios bordering on the specified limits. For these specimens, the column capacity will be affected by w/t ratios for some values of flat with w.

Specimens of nominal size 3x3x3/8 in. have their w/t ratios below the specified limt. The column capacity for these specimens will not be affected by w/t ratios.

Tables 5.5a to 5.9b list the calculated values and their ratios with experimental values. In all computations, the experimental loads have been taken as the base for comparison.

5.5.2 CAN/CSA-S37-M86

The Canadian Standard S37 refers to CAN3-S16.1 [Steel Structures for Buildings (Limit States Design)] for factored axial compression resistance formulae. These are adopted from the column design curve no.2 of the Structural Stability Research Council Proposals. The formulae are mainly derived for W shapes rolled in Canada and are applicable for other doubly symmetric hot-rolled sections. The members in the intermediate range of slenderness are treated as beam-columns with an initial out of straightness and residual stresses. These formulae are not based on test results obtained for singly symmetric sections such as angles. For such members, the standard advises the designer to check whether torsional-flexural buckling is critical. The standard, however does not give any guidelines for the procedures to be adopted for such checking. S16.1 limits the applicable w/t ratio to $200/\sqrt{F_y}$. The proposed amendment to S37 seeks to include the sections with w/t ratio greater than this limit by introducing a reduction factor.

The column capacities are calculated using the formulae given in Clause 13.3.1 of S16.1 and the proposed amendment to S37 with a ϕ value of 1.0. The results are shown in Table 5.5a. The values calculated using flat width equal to the width of bent portion 'b' of the schifflerized angle are closest to the test results. However, the values are higher than the test results for specimens S5-5/16-1 to 3. The same trend is seen in the values computed using the nominal dimensions (Table 5.5b). These values are slightly less than the values calculated for actual dimensions. In this table, all predicted values (except S5-5/16-1) are smaller than the experimental values.

The corresponding values scaled down with a resistance factor of $\phi = 0.90$ are given in Tables 5.5c and 5.5d. All these values for both actual and nominal dimensions are less than the test results. It may be noted that for schifflerized angles which failed by flexural buckling, the load capacity predicted by the specification is conservative by 15% to 20%. Even though the formulae given in the specification are not intended for torsional-flexural buckling, these formulae predict column strengths which are close to the test results. From these results it appears that for schifflerized angles, the Canadian standard S37 with the proposed amendment to account for the sections with w/t ratios larger than the limiting value gives acceptably good results. The applicable leg width can be taken as the width of the bent portion of the schifflerized leg. It should be noted that, CAN3-S16.1-M84 underestimated the flexural buckling strength of schifflerized angles.

5.5.3 ASCE Manual No. 52 (1988)

The widely used "Guide for Design of Steel Transmission Towers " adopts the Structural Stability Research Council formula for ultimate strength of the centrally loaded columns in the inelastic range. For the elastic range, it depends on the Euler formula. The manual justifies the use of these formulae using experimental data. Steel Transmission towers are routinely subjected to full scale testing. The data gathered by ASCE from these tests concerns with members with L/r ratios up to 50. Eventhough the SSRC curves are developed primarily for members with somewhat higher L/r ratios, the manual accepts their use for towers because of their agreement with data from tower testing. The manual accounts for local buckling by derating the critical strength based on the value of w/t ratio.

The column strengths predicted by ASCE manual using actual dimensions are given in Table 5.6a. Corresponding values for nominal dimensions are listed in Table 5.6b. Although the manual specifies that the applicable flat width for w/t ratio is the width from the toe of the angle to the edge of fillet for a 90° angle, the capacities for schifflerized angles are calculated using all four alternative possible flat widths. The capacity calculated using a flat width equal to the bent portion of the schifflerized leg is almost always greater than the test result. The corresponding value calculated using nominal leg width is lower. The loads calculated using nominal properties are lower than the corresponding values for actual properties. For flexural buckling, the predicted values are higher by up to 9% when compared to the test results. This happens only in the case of the specimens with nominal size of 3x3x3/8 in.. For this size, the slenderness ratios exceed slightly the limit set for the slender columns. For such cases, the member strength is calculated using elastic Euler buckling formula, whereas the actual member failed by inelastic buckling. This discrepancy can account for the slightly higher loads predicted by the ASCE formula.

From the above results, it can be seen that the ASCE manual predicts column capacities that are in good agreement with the test results for flexural buckling. For torsional-flexural failure of schifflerized angles, the manual predicts higher capacities. This can be greatly reduced or avoided by taking the applicable flat width as the nominal leg width instead of the width as defined in ASCE Manual No.52 for computing w/t ratios.

5.5.4 AISC-LRFD-1986

The AISC load and resistance factor design for concentrically loaded columns is based on a modified approach compared to the allowable stress design (ASD). The ASD is based on SSRC column curve no.2. This column curve is fitted with an exponential equation in the inelastic flexural buckling range. This equation predicts slightly lower values than the corresponding ASD formula. The elastic flexural buckling is represented by a modified Euler equation. Unlike CSA-S37 or ASCE manual, the AISC specifically accounts for torsional-flexural buckling. It uses the classical approach for determining the elastic torsional-flexural buckling capacity. The upper limit for elastic buckling is set at 50% of the yield stress. When the stress exceeds this value, the torsional buckling formulae are modified by the use of an equivalent slenderness factor. In both flexural and torsional-flexural buckling modes, the local plate failure is accounted for, by a modification factor which is a function of the w/t ratio. The limiting ratio however is slightly less than the corresponding limit set by ASCE or CSA.

Column capacities computed using various possible values of flat width for actual and nominal properties are listed in Tables 5.7a and 5.7b. The value of ϕ is taken as 1.0 for these tables. The corresponding loads for ϕ equal to 0.85 are shown in Tables 5.7c and 5.7d. All the values predicted in all these tables are less than the corresponding test results. The computed results have less scatter when compared to the values of either CSA or ASCE. The level of accuracy is consistent between members that failed in torsional-flexural and flexural failure modes. The nominal properties predicted loads that are slightly less than those for actual properties.

An examination of these values shows that the loads computed using a flat width equal to the bent portion of the schifflerized angle leg are closest yet less than the experimental failure loads. Therefore the width b (Fig. 1.3) can be used for all computations with AISC formulae.

5.5.5 BS 5950 : Part 1 : 1985

In the British practice, the critical stresses for different slenderness ratios and yield stresses are computed using the long-standing Perry-Robertson formulae. The yield stress is modified when the w/t ratio exceeds a limiting value. Loads computed using the provisions of the British practice are given in Table 5.8a and 5.8b for actual and nominal properties respectively. All the loads predicted are less than the corresponding test loads. The loads for nominal properties are slightly less than the corresponding loads for actual properties. The predicted loads have more scatter when compared with the predictions of AISC formulae. The values predicted for torsional-flexural buckling are closer to the failure loads than the values for flexural buckling. An examination of the values shows that the loads computed using a flat width equal to the bent portion of the schifflerized leg are closest to the experimental loads. Hence the width b (Fig. 1.3) can be taken as the applicable flat width for w/t ratio.

5.5.6 ECCS Recommendations

The European practice follows design strength procedures established from the data collected from several tower testing programs throughout Europe. The formulae are specifically designed for angles in tranmission towers and are different from the corresponding formulae used in general steel construction. The design buckling stresses are higher than the normal steel design practice because, these structures are tested to failure and in this sense are the best understood steel structures for the designers. The ECCS non-dimensional buckling curve is computed with an initial sinusoidal imperfection of 1/1000 of the length. It does not directly include the effect of torsional-flexural buckling. The plate buckling is considered by derating the applicable critical stress when w/t ratio exceeds a limiting value. The nominal leg width is used for computing w/t ratio. The limiting ratio however, is set at $260/\sqrt{F_y}$ instead of a value close to $200/\sqrt{F_y}$ as is the case with North American practice.

The column capacities calculated using various possible flat widths for both nominal and actual properties are listed in Tables 5.9a and 5.9b. It can be readily seen that the ECCS recommendations give excellent predictions for flexural buckling. The values are closest yet less than the experimental values when compared to the other standard specifications. The loads for torsional-flexural buckling failure however, are higher by up to 20% when compared to the experimental loads. The higher predictions of ECCS formulae for torsional mode can perhaps be explained by the higher limiting w/t ratio when compared to the North American practice. From these results, it can be seen that the applicable flat width is the nominal leg width of the schifflerized angle ("a+b " of Fig. 1.3).

Chapter 6
CONCLUSIONS AND RECOMMENDATIONS

In the present investigation, the behaviour of schifflerized hot-rolled angles under concentric loading is studied. Special emphasis is placed on determining the applicable flat width to be used for computing the w/t ratio which is used to estimate the strength of axially loaded compression members.

6.1 Conclusions

Based on the results and observations of the present investigation, the following conclusions are arrived at:

1. The compression tests carried out on the schifflerized angles under concentric loads have yielded data for members failing in flexural and torsional-flexural buckling modes. The data obtained is found to be suitable for calibrating design procedures.
2. In general, column strengths computed using various standard specifications differ appreciably from each other.
   a. The proposed amendment for CAN/CSA-S37-M86 predicts schifflerized angle strengths close to actual test results for torsional-flexural buckling. For flexural buckling, the provisions of CAN3-S16.1-M84 which are referenced by CAN/CSA-S37-M86 underestimate the schifflerized angle capacities.

b. ASCE Manual No. 52 predicts flexural buckling loads that are very close to test results. But for torsional-flexural buckling, the manual overestimates the failure loads of schifflerized angles.

c. AISC-LRFD-1986 predicts loads that are in good agreement with test results for both flexural and torsional-flexural buckling modes. There is less scatter between predicted and experimental failure loads compared to other standards.

d. BS 5950 : Part 1 : 1985 predicts flexural and torsional-flexural buckling loads which are in reasonable agreement with the test data. In no case, does the standard overestimate the member capacity. The load estimates have greater scatter when compared to AISC predictions.

e. ECCS Recommendations predict column strengths in flexural buckling which are in excellent agreement with test results. However, for torsional-flexural buckling the recommendations overestimate the column strength.

3. The recommended flat width to be used in the computation of w/t ratio for various standard specifications is as follows :

a. For CAN/CSA-S37-M86, w = width of the bent portion of the schifflerized angle (dimension *b* of Fig. 1.3).

b. For ASCE Manual No. 52 (1988), w = nominal leg width.

c. For AISC-LRFD-1986, w = width of the bent portion of the schifflerized angle (dimension *b* of Fig. 1.3).

d. For BS 5950 : Part 1 : 1985, w = width of the bent portion of the schifflerized angle (dimension *b* of Fig. 1.3).

e. For ECCS Recommendations (1985), w = nominal leg width.

4. The finite element model designed for analyzing the schifflerized angles gives reasonably good estimation of the failure loads. The procedure can be used to predict failure loads of schifflerized angles when actual testing cannot be carried out.

5. Using finite element analysis, it is estimated that the residual stresses reduce the strength of the the schifflerized angle by approximately 20%. Through the thickness variation of the residual stresses due to schifflerization process reduces the buckling load by approximately 2% to 4%.

6.2 Recommendations for Further Research

Based on the experience gained in the present investigation, it is recommended that the following issues may be considered for future research:

1. Keeping in view of the limited nature of the present experimental investigation, more tests can be conducted for different sizes of schifflerized angles.

2. 60° angles manufactured directly by hot-rolling can be studied to find the similarities and differences with schifflerized angles.

3. The residual stress patterns as used in the present study are based on the recommendations of ECCS. Although the results obtained using these recommendations seem to be in good agreement with the test results, it is

desirable to determine experimentally the residual stress distribution across the section and through the thickness of the legs.

4. The test setup used is found to be good for flexural buckling. However, a better design for end fixtures is desirable for members failing in torsional-flexural buckling mode.

REFERENCES

1. ABAQUS Version 4.8, 1989, *User's Manual. Parts 1, 2, 3 & 4*, Hibbitt, Karlsson & Sorensen, Inc., 100 Medway st., Providence, RI 02906-4402, USA.
2. ASCE Manuals and Reports on Engineering Practice No. 52, *Guide for Design of Steel Transmission Towers*. Second edition, American Society of Civil Engineers, New York, 1987.
3. American Institute of Steel Construction, *Load and Resistance Factor Design Specification for Structural Steel Buildings*. Chicago, Illinois, 1986.
4. Bergan, P.G., Horrigmoe, G., Krakeland, B. and Soreide, T.H., *Solution Techniques for Non-Linear Finite Element Problems*. Int. Journal for Numerical Methods in Engineering, Vol.12, 1677-1696 (1978).
5. Bleich, F., and Bleich, H., *Bending, Torsion and Buckling of Bars Composed of Thin Walls*, 2nd Congress, Int.Assn. for Bridge and Structural Engineering, Berlin, 1936.
6. Bleich, F., *Buckling Strength of Metal Structures*. McGraw-Hill Book Company, New York, 1952.
7. BS 5950 : Part 1 : 1985, *British Standard Structural use of Steelwork in Building, Part 1. Code of practice for design in simple and continuous*

construction : hot-rolled sections. British Standards Institution, London, UK, 1985.

8. CAN/CSA S37-M86, *Antennas, Towers and Antenna Supporting Structures.* Canadian Standards Association, Rexdale, Ont., 1986.
9. CAN3-S16.1-M84, *Steel Structures for Buildings (Limit States Design).* Canadian Standards Association, Rexdale, Ont., 1984.
10. Chajes, A., and Winter George., *Torsional-Flexural Buckling of Thin-Walled Members.* ASCE Journal of Structural Division, vol.91, ST4, Aug.1965, pp.103-124.
11. Chajes, A., *Principles of Structural Stability Theory.* Prentice-Hall Inc., Engelwood Cliffs, New Jersey, 1974.
12. Crisfield, M.A., *Snap-Through and Snap-back response in Concrete Structures and the Dangers of Under-Integration.* Int. Journal for Numerical Methods in Engineering. vol. 22, 751-767 (1986).
13. ECCS-European Convention for Constructional Steelwork Technical Committee 8- Structural Stability (WG 8.1 - Components) *Recommendations for Angles in Lattice Towers ,* Publication No. 39, 1985.
14. El-Darwish, I.A., Johnston, B.G., *Torsion of Structural Shapes.* ASCE Journal of Structural Division, vol.91, No.ST1, Feb.1965, pp.203-227.
15. Goodier, J.N., *Flexural-Torsional Buckling of Bars of Open Section.* Cornell University Engineering Expt. Station Bulletin No.28, 1942.
16. Haaijer, G., Carskaddan, P.S. and Grubb, M.A., *Eccentric Load Test of Angle Column Simulated with MSC/NASTRAN Finite Element Program.*

Paper presented at the Annual meeting of Structural Stability Research Council, Chicago, 1981.

17. Ishida, A., *Experimental Study on Column Carrying Capacity of 'SHY' Steel Angles* , Yawata Technical Report No.265, Yawata Iron and Steel Co. Ltd., Tokyo, Japan, 1968, pp.8564-8582 and 8761-8763.

18. Johnson, J.B., Bryan, C.W. and Turneaure, F.E., *Theory and Practice of Modern Framed Structures,* 8th ed., John Wiley & Sons, Inc., New York, N.Y., 1905, p.561.

19. Johnston, Bruce G., *Column Buckling Theory : Historic Highlights.*, ACSE Journal of Structural Engineering, vol.109, No.9, Sept.1983, pp.2086-2096.

20. Kennedy, J.B. and Madugula, Murty K.S., *Buckling of Steel Angle and Tee Struts,* ASCE Journal of Structural Diivison, ASCE 98 (ST11), Nov.1972, pp.2507-2522.

21. Kennedy, J.B. and Madugula, Murty K.S., *Buckling of Single and Compound Angles,* Chapter 6 in "Axially Compressed Structures : Stability and Strength", R.Narayanan, ed., Applied Science Publishers Ltd., Barking, England, 1982, pp.181-216.

22. Lipson, S.L. and Haque, M.I., *Elasto-Plastic Analysis of Single-Angle Bolted-Welded Connections Using the Finite Element Method,* Computers & Structures vol.9, pp.533-545, 1978.

23. Lundquist, E.E. and Fligg, C.M., *A Theory for Primary Failure of Straight Centrally Loaded Columns,* NASA Technical Report No.582, 1937.

24. Madugula, Murty K.S. and Kennedy, John B., *Single and Compound Angle Members : Structural Analysis and Design* , Elsevier Applied Science Publishers, London, 1985.

25. Matthies, H., Strang, G., *The Solution of Nonlinear Finite Element Equations,* Int.Journal for Numerical Methods in Engineering, vol.14, 1613-1626 (1979).

26. Powel, G., and Simons, J., *Improved Iteration Strategy for Nonlinear Structures,* Int. Journal for Numerical Methods in Engineering, vol.17, 1455-1467 (1981).

27. Shanley, F.R., *Inelastic Column Theory,* Journal of Aeronautical Science, vol.14, No.5, 1947, pp.261-267.

28. Short, J., *The Buckling of Single Angles About the xx and vv Axes,* Second International Colloquium on Stability of Steel Structures, Liege, April.1977, Final Report.

29. SSRC-Structural Stability Research Council, *Guide to Stability Design Criteria for Metals Structures,* 4th ed., Galambos, Theodore V., editor., John Wiley & Sons, 1988.

30. Templin, R.L., Strum, R.G., Hartman, E.C. and Holt, M., *Technical Report No.1.* Aluminium Company Research Labs, New Kensington, 1938.

31. Timoshenko, S.P., *Theory of Bending, Torsion and Buckling of Thin-Walled Members of Open Cross-Section,* Journal of the Franklin Institute., Philadelphia, Pa, USA, 239(3), 201-219; 239(4), 249-268; 239(5), 343-361.

32. Timoshenko, S.P. and Gere, J.M., *Theory of Elastic Stability*, McGraw-Hill Book Comapny, 1970.

33. Todhunter, I. and Pearson, K., *A History of the Theory of Elasticity and of Strength of Materials*, Dover Publications, 1960 (originally published by Cambridge Univ. Press 1893).

34. Vlasov, V.Z., *Thin-walled Elastic Beams*, Translated from Russian by Israel Program for Scientific Translations, 1961.

35. Wakabayashi, M. and Nonaka, T., *On the Buckling Strength of Angles in Transmission Towers*, Bulletin of Disaster Prevention Institute, Kyoto University, Kyoto, Japan, vol.15, Part 2, No.91., Nov.1965, pp.1-18.

36. Wilhoite, G., Zandonini, R. and Zavelani, A., *Behaviour and Strength of Angles in Compression: An Experimental Investigation*, ASCE Annual Convention and Structures Congress, San Francisco, Oct.1984.

37. Yokoo, Y., Wakabayashi, M. and Nonaka, T., *An Experimental Study on Buckling of Angles*, Yawata Technical Report No.265, Dec.1968, pp.8543-8563 and 9759-8760, Yawata Iron and Steel Co., Ltd., Tekko Building, Tokyo, Japan.

TABLES

Table 2.1 Non-dimensional Buckling Curve based on ECCS Recommendations

VALUES OF NON-DIMENSIONAL COLUMN CURVE
EQUATION $\bar{\lambda} = \Lambda$

λ	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
.2	1.0000	.9987	.9974	.9961	.9947	.9934	.9920	.9907	.9893	.9879
.3	.9865	.9850	.9836	.9821	.9806	.9791	.9776	.9761	.9745	.9729
.4	.9713	.9696	.9679	.9662	.9644	.9626	.9608	.9589	.9570	.9551
.5	.9531	.9510	.9489	.9468	.9446	.9423	.9400	.9376	.9352	.9327
.6	.9301	.9274	.9247	.9219	.9190	.9160	.9129	.9097	.9064	.9030
.7	.8995	.8959	.8921	.8883	.8843	.8802	.8759	.8715	.8670	.8623
.8	.8575	.8525	.8474	.8421	.8366	.8310	.8253	.8193	.8133	.8070
.9	.8007	.7941	.7875	.7807	.7737	.7667	.7595	.7522	.7449	.7374
1.0	.7298	.7222	.7146	.7068	.6991	.6913	.6834	.6756	.6678	.6600
1.1	.6521	.6444	.6366	.6289	.6212	.6136	.6060	.5985	.5910	.5837
1.2	.5764	.5691	.5620	.5549	.5479	.5410	.5342	.5274	.5208	.5142
1.3	.5078	.5014	.4951	.4889	.4828	.4768	.4709	.4651	.4593	.4536
1.4	.4481	.4426	.4372	.4319	.4266	.4215	.4164	.4114	.4065	.4017
1.5	.3969	.3922	.3876	.3831	.3786	.3742	.3699	.3657	.3615	.3573
1.6	.3533	.3493	.3454	.3415	.3377	.3339	.3302	.3266	.3230	.3195
1.7	.3160	.3126	.3093	.3060	.3027	.2995	.2963	.2932	.2901	.2871
1.8	.2841	.2812	.2783	.2755	.2727	.2699	.2672	.2645	.2619	.2593
1.9	.2567	.2542	.2517	.2492	.2468	.2444	.2420	.2397	.2374	.2351
2.0	.2329	.2307	.2286	.2264	.2243	.2222	.2202	.2182	.2162	.2142
2.1	.2122	.2103	.2084	.2066	.2047	.2029	.2011	.1993	.1976	.1959
2.2	.1942	.1925	.1908	.1892	.1876	.1860	.1844	.1828	.1813	.1798
2.3	.1783	.1768	.1753	.1739	.1724	.1710	.1696	.1683	.1669	.1656
2.4	.1642	.1629	.1616	.1603	.1591	.1578	.1566	.1554	.1541	.1530
2.5	.1518	.1506	.1494	.1483	.1472	.1461	.1450	.1439	.1428	.1417
2.6	.1407	.1396	.1386	.1376	.1366	.1356	.1346	.1336	.1326	.1317
2.7	.1307	.1298	.1289	.1280	.1270	.1261	.1253	.1244	.1235	.1227
2.8	.1218	.1210	.1201	.1193	.1185	.1177	.1169	.1161	.1153	.1145
2.9	.1138	.1130	.1122	.1115	.1108	.1100	.1093	.1086	.1079	.1072
3.0	.1065	.1058	.1051	.1044	.1038	.1031	.1024	.1018	.1011	.1005

TABLE 5.1a

PROPERTIES OF TEST SPECIMENS (NOMINAL SIZE : 5x5x5/16 in.)

PROPERTY	NOMINAL	S5-5/16-1	S5-5/16-2	S5-5/16-3
Leg width (mm)	127.0	125.4	126.2	125.4
a (mm)	25.0	25.0	25.0	25.0
b (mm)	102.0	100.4	101.2	100.4
t (mm)	7.9	7.9	7.9	7.9
c (mm)	13.0	13.0	13.0	13.0
Area (mm^2)	1953.1	1907.5	1926.4	1907.4
u_o (mm)	50.2	49.6	49.9	49.5
I_{max} 10^6 (mm^4)	3.022	2.886	2.948	2.886
I_{min} 10^6 (mm^4)	1.799	1.712	1.752	1.712
I_{ps} 10^6 (mm^4)	9.746	9.282	9.494	9.280
J 10^4 (mm^4)	4.102	3.918	3.985	3.918
C_w 10^9 (mm^6)	0.517	0.482	0.496	0.482
R_1 (mm)	39.3	38.9	39.1	38.9
R_2 (mm)	30.4	30.0	30.2	30.0
R_q (mm)	21.3	21.3	21.3	21.3
R_e (mm)	19.7	19.7	19.7	19.7
Length (mm)	1654.2	1654.2	1654.2	1654.2

** For explanations refer Fig. 1.3 and Notation

TABLE 5.1b

PROPERTIES OF TEST SPECIMENS (NOMINAL SIZE : 4x4x1/4 in.)

PROPERTY	NOMINAL	S4-1/4-1	S4-1/4-2	S4-1/4-3
Leg width (mm)	101.6	100.8	100.8	101.0
a (mm)	24.0	24.0	24.0	24.0
b (mm)	77.6	76.8	76.8	77.0
t (mm)	6.4	6.2	6.2	6.2
c (mm)	10.0	10.0	10.0	10.0
Area (mm^2)	1250.0	1217.3	1217.7	1222.1
u_o (mm)	39.7	39.3	39.3	39.4
I_{max} (10^6 mm^4)	1.293	1.244	1.244	1.253
I_{min} (10^6 mm^4)	0.727	0.697	0.697	0.702
I_{ps} (10^6 mm^4)	3.986	3.824	3.825	3.854
J (10^4 mm^4)	1.680	1.575	1.576	1.588
C_w (10^9 mm^6)	0.136	0.125	0.125	0.127
R_u (mm)	32.2	32.0	32.0	32.0
R_v (mm)	24.1	23.9	23.9	24.0
R_q (mm)	21.3	21.0	21.0	21.0
R_e (mm)	18.9	18.7	18.8	18.8
Length (mm)	1654.2	1654.2	1654.2	1654.2

** For explanations refer Fig. 1.3 and Notation

TABLE 5.1c

PROPERTIES OF TEST SPECIMENS (NOMINAL SIZE : 3.5x3.5x5/16 in.)

PROPERTY	NOMINAL	S3.5-5/16-1	S3.5-5/16-2	S3.5-5/16-3
Leg width (mm)	88.9	90.1	90.1	90.1
a (mm)	25.0	25.0	25.0	25.0
b (mm)	63.9	65.1	65.1	65.1
t (mm)	7.9	8.0	[illegible].0	8.0
c (mm)	10.0	10.0	10.0	10.0
Area (mm^2)	1348.3	1369.6	1371.4	1373.8
u_c (mm)	33.8	34.4	34.4	34.4
I_{max} (10^6 mm^4)	1.081	1.125	1.126	1.128
I_{min} (10^6 mm^4)	0.577	0.603	0.604	0.605
I_{ps} (10^6 mm^4)	3.202	3.344	3.348	3.354
J (10^4 mm^4)	2.832	2.887	2.899	2.915
C_w (10^9 mm^6)	0.170	0.178	0.179	0.180
R_u (mm)	28.3	28.7	28.7	28.7
R_v (mm)	20.7	21.0	21.0	21.0
R_q (mm)	30.8	30.4	30.5	30.5
R_e (mm)	22.6	22.6	22.7	22.7
Length (mm)	1654.2	1654.2	1654.2	1654.2

** For explanations refer Fig. 1.3 and Notation

TABLE 5.1d

PROPERTIES OF TEST SPECIMENS (NOMINAL SIZE : 3x3x3/8 in.SET-A)

PROPERTY	NOMINAL	S3-3/8-1	S3-3/8-2	S3-3/8-3
Leg width (mm)	76.2	76.2	77.4	77.4
a (mm)	26.0	26.0	26.0	26.0
b (mm)	50.2	50.2	51.4	51.4
t (mm)	9.5	9.6	9.6	9.6
c (mm)	8.0	8.0	8.0	8.0
Area (mm^2)	1360.9	1368.2	1391.3	1391.1
u_o (mm)	28.1	28.1	28.6	28.6
I_{max} (10^6 mm^4)	0.814	0.818	0.855	0.855
I_{min} (10^6 mm^4)	0.405	0.407	0.428	0.428
I_{ps} (10^6 mm^4)	2.291	2.301	2.418	2.419
J (10^4 mm^4)	4.116	4.186	4.258	4.256
C_w (10^9 mm^6)	0.175	0.178	0.187	0.187
R_u (mm)	24.5	24.5	24.8	24.8
R_v (mm)	17.2	17.2	17.5	17.5
R_q (mm)	43.9	44.1	43.4	43.4
R_e (mm)	22.6	22.6	22.8	22.8
Length (mm)	1654.2	1654.2	1654.2	1654.2

** For explanations refer Fig. 1.3 and Notation

TABLE 5.1e

PROPERTIES OF TEST SPECIMENS (NOMINAL SIZE : 3x3x3/8 in.SET-B)

PROPERTY	NOMINAL	S3-3/8-4	S3-3/8-5	S3-3/8-6
Leg width (mm)	76.2	76.9	77.1	77.4
a (mm)	26.0	26.0	26.0	26.0
b (mm)	50.2	50.9	51.1	51.4
t (mm)	9.5	9.6	9.6	9.6
c (mm)	8.0	8.0	8.0	8.0
Area (mm^2)	1360.9	1381.6	1385.6	1391.1
u_c (mm)	28.1	28.3	28.4	28.6
I_{max} (10^6 mm^4)	0.814	0.840	0.846	0.855
I_{min} (10^6 mm^4)	0.405	0.419	0.423	0.428
I_{ps} (10^6 mm^4)	2.291	2.369	2.389	2.418
J (10^4 mm^4)	4.116	4.227	4.240	4.256
C_w (10^6 mm^6)	0.175	0.183	0.185	0.187
R_u (mm)	24.5	24.7	24.7	24.8
R_v (mm)	17.2	17.4	17.5	17.5
R_q (mm)	43.9	43.7	43.6	43.4
R_e (mm)	22.6	22.8	22.8	22.8
Length (mm)	1654.2	1654.2	1654.2	1654.2

** For explanations refer Fig. 1.3 and Notation

TABLE 5.1f

PROPERTIES OF TEST SPECIMENS (NOMINAL SIZE : 3x3x1/4 in.)

PROPERTY	NOMINAL	S3-1/4-1	S3-1/4-2	S3-1/4-3
Leg width (mm)	76.2	77.0	77.0	76.7
a (mm)	24.0	24.0	24.0	24.0
b (mm)	52.2	53.0	53.0	52.7
t (mm)	6.4	6.2	6.2	6.2
r (mm)	8.0	8.0	8.0	8.0
Area (mm^2)	927.4	920.6	918.1	915.7
u_o (mm)	28.8	29.1	29.1	29.0
I_{max} 10^6 (mm^4)	0.570	0.578	0.577	0.571
I_{min} 10^6 (mm^4)	0.288	0.293	0.293	0.289
I_{ps} 10^6 (mm^4)	1.627	1.653	1.649	1.631
J 10^4 (mm^4)	1.247	1.191	1.181	1.182
C_w 10^8 (mm^6)	0.055	0.054	0.054	0.053
R_x (mm)	24.8	25.1	25.1	25.0
R_y (mm)	17.6	17.9	17.9	17.8
R_q (mm)	28.6	27.8	27.7	27.9
R_o (mm)	20.4	20.2	20.2	20.2
Length (mm)	1654.2	1654.2	1654.2	1654.2

** For explanations refer Fig. 1.3 and Notation

TABLE 5.2
MECHANICAL PROPERTIES OF TENSILE COUPONS

Nominal Size (in.)		Yield Stress (MPa) (2% offset)	Ultimate Stress (MPa)
5x5x5/16	#1	333	490
5x5x5/16	#2	333	487
4x4x1/4	#1	356	527
4x4x1/4	#2	356	531
3.5x3.5x5/16	#1	369	530
3.5x3.5x5/16	#2	369	528
3x3x3/8	#1	480	620
3x3x3/8	#2	470	616
3x3x1/4	#1	363	542
3x3x1/4	#2	363	547

TABLE 5.3
FAILURE LOADS OF TEST SPECIMENS

SPECIMEN	SLENDERNESS RATIO	COLUMN SLENDERNESS PARAMETER	FAILURE LOAD (kN)	FAILURE STRESS (MPa)
S5-5/16-1	55	0.716	422	221
S5-5/16-2	55	0.711	446	232
S5-5/16-3	55	0.716	440	231
S4-1/4-1	69	0.929	278	228
S4-1/4-2	69	0.929	286	235
S4-1/4-3	69	0.927	311	254
S3.5-5/16-1	79	1.078	350	256
S3.5-5/16-2	79	1.078	366	267
S3.5-5/16-3	79	1.078	350	255
S3-3/8-1	96	1.488	287	210
S3-3/8-2	94	1.463	287	206
S3-3/8-3	94	1.463	288	207
S3-3/8-4	95	1.473	278	201
S3-3/8-5	95	1.469	287	207
S3-3/8-6	94	1.463	289	208
S3-1/4-1	93	1.257	187	203
S3-1/4-2	93	1.256	217	236
S3-1/4-3	93	1.262	208	227

TABLE 5.4
RESULTS OF FINITE ELEMENT ANALYSIS FOR TEST SPECIMENS

SPECIMEN	KL/r	COLUMN NON-DIMENSIONAL SLENDERNESS PARAMETER	EXPERI-MENTAL LOAD (kN)	FINITE ELEMENT LOAD (kN)	RATIO OF F.E.M. AND EXPERIME-NTAL LOADS
S5-5/16-1	55	0.716	422	451	1.06
S5-5/16-2	55	0.711	446	455	1.02
S5-5/16-3	55	0.716	440	451	1.03
S4-1/4-1	69	0.929	278	262	0.94
S4-1/4-2	69	0.929	286	262	0.93
S4-1/4-3	69	0.927	311	263	0.85
S3.5-5/16-1	79	1.078	350	336	0.96
S3.5-5/16-2	79	1.078	366	336	0.92
S3.5-5/16-3	79	1.078	350	337	0.96
S3-3/8-1	96	1.488	287	257	0.90
S3-3/8-2	94	1.463	287	261	0.91
S3-3/8-3	94	1.463	288	261	0.91
S3-3/8-4	95	1.473	278	260	0.94
S3-3/8-5	95	1.469	287	260	0.91
S3-3/8-6	94	1.463	289	261	0.90
S3-1/4-1	93	1.257	187	175	0.94
S3-1/4-2	93	1.256	217	175	0.81
S3-1/4-3	93	1.262	208	174	0.84

TABLE 5.5a
COMPARISON OF EXPERIMENTAL FAILURE LOADS
AND LOADS CALCULATED ACCORDING TO CAN/CSA-S37-M86
Strength based on actual dimensions, PHI=1.0

SPECIMEN	P TEST (kN)	CASE I LOAD (kN)	CASE I RATIO	CASE II LOAD (kN)	CASE II RATIO	CASE III LOAD (kN)	CASE III RATIO	CASE IV LOAD (kN)	CASE IV RATIO
S5-5/16-1	422.	449.	1.06	435.	1.03	393.	0.93	366.	0.87
S5-5/16-2	446.	453.	1.02	440.	0.99	397.	0.89	369.	0.83
S5-5/16-3	440.	449.	1.02	435.	0.99	393.	0.89	366.	0.83
S4-1/4-1	278.	265.	0.95	250.	0.90	227.	0.82	212.	0.76
S4-1/4-2	286.	265.	0.93	250.	0.87	228.	0.80	212.	0.74
S4-1/4-3	311.	267.	0.86	251.	0.81	229.	0.74	213.	0.69
S3.5-5/16-1	350.	280.	0.80	280.	0.80	280.	0.80	274.	0.78
S3.5-5/16-2	366.	280.	0.77	280.	0.77	280.	0.77	275.	0.75
S3.5-5/16-3	350.	281.	0.80	281.	0.80	281.	0.80	275.	0.79
S3-3/8-1	287.	231.	0.81	231.	0.81	231.	0.81	231.	0.81
S3-3/8-2	287.	241.	0.84	241.	0.84	241.	0.84	241.	0.84
S3-3/8-3	286.	241.	0.84	241.	0.84	241.	0.84	241.	0.84
S3-3/8-4	278.	237.	0.85	237.	0.85	237.	0.85	237.	0.85
S3-3/8-5	287.	238.	0.83	238.	0.83	238.	0.83	238.	0.83
S3-3/8-6	289.	241.	0.83	241.	0.83	241.	0.83	241.	0.83
S3-1/4-1	187.	150.	0.80	150.	0.80	148.	0.79	144.	0.77
S3-1/4-2	217.	150.	0.69	150.	0.69	147.	0.68	144.	0.66
S3-1/4-3	208.	149.	0.72	149.	0.72	146.	0.70	143.	0.69

** note : case (I):w=b; (II):w=a+b-t-c; (III):w=a+b-t; (IV):w=a+b
** See Fig. 1.3 for notation;RATIO='Load P as per spec.'/'P Test'

TABLE 5.5b
COMPARISON OF EXPERIMENTAL FAILURE LOADS
AND LOADS CALCULATED ACCORDING TO CAN/CSA-S37-M86
Strength based on nominal dimensions, PHI=1.0

SPECIMEN	P TEST (kN)	CASE I LOAD (kN)	CASE I RATIO	CASE II LOAD (kN)	CASE II RATIO	CASE III LOAD (kN)	CASE III RATIO	CASE IV LOAD (kN)	CASE IV RATIO
S5-5/16-1	422.	439.	1.04	428.	1.01	390.	0.92	366.	0.87
S5-5/16-2	446.	439.	0.99	428.	0.96	390.	0.87	366.	0.82
S5-5/16-3	440.	439.	1.00	428.	0.97	390.	0.89	366.	0.83
S4-1/4-1	278.	258.	0.93	244.	0.88	226.	0.81	214.	0.77
S4-1/4-2	286.	258.	0.90	244.	0.85	226.	0.79	214.	0.75
S4-1/4-3	311.	258.	0.83	244.	0.79	226.	0.73	214.	0.69
S3.5-5/16-1	350.	251.	0.72	251.	0.72	251.	0.72	251.	0.72
S3.5-5/16-2	366.	251.	0.69	251.	0.69	251.	0.69	251.	0.69
S3.5-5/16-3	350.	251.	0.72	251.	0.72	251.	0.72	251.	0.72
S3-3/8-1	287.	219.	0.76	219.	0.76	219.	0.76	219.	0.76
S3-3/8-2	287.	219.	0.76	219.	0.76	219.	0.76	219.	0.76
S3-3/8-3	288.	219.	0.76	219.	0.76	219.	0.76	219.	0.76
S3-3/8-4	278.	219.	0.79	219.	0.79	219.	0.79	219.	0.79
S3-3/8-5	287.	219.	0.76	219.	0.76	219.	0.76	219.	0.76
S3-3/8-6	289.	219.	0.76	219.	0.76	219.	0.76	219.	0.76
S3-1/4-1	187.	140.	0.75	140.	0.75	140.	0.75	139.	0.74
S3-1/4-2	217.	140.	[illegible].65	140.	0.65	140.	0.65	139.	0.64
S3-1/4-3	208.	140.	0.67	140.	0.67	140.	0.67	139.	0.67

** note : case (I):w=b; (II):w=a+b-t-c; (III):w=a+b-t; (IV):w=a+b
** See Fig. 1.3 for notation;RATIO='Load P as per spec.'/'P Test'

TABLE 5.5c
COMPARISON OF EXPERIMENTAL FAILURE LOADS
AND LOADS CALCULATED ACCORDING TO CAN/CSA-S37-M86
Strength based on actual dimensions, PHI=0.9

SPECIMEN	P TEST (kN)	CASE I LOAD (kN)	CASE I RATIO	CASE II LOAD (kN)	CASE II RATIO	CASE III LOAD (kN)	CASE III RATIO	CASE IV LOAD (kN)	CASE IV RATIO
S5-5/16-1	422.	404.	0.96	392.	0.93	354.	0.84	330.	0.79
S5-5/16-2	446.	408.	0.91	396.	0.89	357.	0.80	332.	0.75
S5-5/16-3	440.	404.	0.92	392.	0.89	354.	0.80	330.	0.75
S4-1/4-1	278.	239.	0.86	225.	0.81	205.	0.74	191.	0.69
S4-1/4-2	286.	239.	0.83	225.	0.79	205.	0.72	191.	0.67
S4-1/4-3	311.	240.	0.77	226.	0.73	206.	0.66	192.	0.62
S3.5-5/16-1	350.	252.	0.72	252.	0.72	252.	0.72	247.	0.71
S3.5-5/16-2	366.	252.	0.69	252.	0.69	252.	0.69	247.	0.68
S3.5-5/16-3	350.	253.	0.72	253.	0.72	253.	0.72	248.	0.71
S3-3/8-1	287.	208.	0.72	208.	0.72	208.	0.72	208.	0.72
S3-3/8-2	287.	217.	0.76	217.	0.76	217.	0.76	217.	0.76
S3-3/8-3	288.	217.	0.75	217.	0.75	217.	0.75	217.	0.75
S3-3/8-4	278.	213.	0.77	213.	0.77	213.	0.77	213.	0.77
S3-3/8-5	287.	215.	0.75	215.	0.75	215.	0.75	215.	0.75
S3-3/8-6	289.	217.	0.75	217.	0.75	217.	0.75	217.	0.75
S3-1/4-1	187.	135.	0.72	135.	0.72	133.	0.71	130.	0.70
S3-1/4-2	217.	135.	0.62	135.	0.62	133.	0.61	130.	0.60
S3-1/4-3	208.	134.	0.64	134.	0.64	132.	0.63	129.	0.62

** note : case (I):w=b; (II):w=a+b-t-c; (III):w=a+b-t; (IV):w=a+b
** See Fig. 1.3 for notation;RATIO='Load P as per spec.'/'P Test'

TABLE 5.5d
COMPARISON OF EXPERIMENTAL FAILURE LOADS
AND LOADS CALCULATED ACCORDING TO CAN/CSA-S37-M86
Strength based on nominal dimensions, PHI=0.9

SPECIMEN	P TEST (kN)	CASE I LOAD (kN)	CASE I RATIO	CASE II LOAD (kN)	CASE II RATIO	CASE III LOAD (kN)	CASE III RATIO	CASE IV LOAD (kN)	CASE IV RATIO
S5-5/16-1	422.	395.	0.94	385.	0.91	351.	0.83	329.	0.78
S5-5/16-2	446.	395.	0.89	385.	0.86	351.	0.79	329.	0.74
S5-5/16-3	440.	395.	0.90	385.	0.88	351.	0.80	329.	0.75
S4-1/4-1	278.	232.	0.83	220.	0.79	203.	0.73	192.	0.69
S4-1/4-2	286.	232.	0.81	220.	0.77	203.	0.71	192.	0.67
S4-1/4-3	311.	232.	0.75	220.	0.71	203.	0.65	192.	0.62
S3.5-5/16-1	350.	226.	0.64	226.	0.64	226.	0.64	226.	0.64
S3.5-5/16-2	366.	226.	0.62	226.	0.62	226.	0.62	226.	0.62
S3.5-5/16-3	350.	226.	0.64	226.	0.64	226.	0.64	226.	0.64
S3-3/8-1	287.	197.	0.69	197.	0.69	197.	0.69	197.	0.69
S3-3/8-2	287.	197.	0.69	197.	0.69	197.	0.69	197.	0.69
S3-3/8-3	288.	197.	0.68	197.	0.68	197.	0.68	197.	0.68
S3-3/8-4	278.	197.	0.71	197.	0.71	197.	0.71	197.	0.71
S3-3/8-5	287.	197.	0.69	197.	0.69	197.	0.69	197.	0.69
S3-3/8-6	289.	197.	0.68	197.	0.68	197.	0.68	197.	0.68
S3-1/4-1	187.	126.	0.67	126.	0.67	126.	0.67	125.	0.67
S3-1/4-2	217.	126.	0.58	126.	0.58	126.	0.58	125.	0.58
S3-1/4-3	208.	126.	0.61	126.	0.61	126.	0.61	125.	0.60

** note : case (I):w=b; (II):w=a+b-t-c; (III):w=a+b-t; (IV):w=a+b
** See Fig. 1.3 for notation;RATIO='Load P as per spec.'/'P Test'

TABLE 5.6a
COMPARISON OF EXPERIMENTAL FAILURE LOADS
AND LOADS CALCULATED ACCORDING TO ASCE MANUAL 52-1988
Strength based on actual dimensions, PHI=1.00

SPECIMEN	P TEST (kN)	CASE I LOAD (kN)	CASE I RATIO	CASE II LOAD (kN)	CASE II RATIO	CASE III LOAD (kN)	CASE III RATIO	CASE IV LOAD (kN)	CASE IV RATIO
S5-5/16-1	422.	511.	1.21	494.	1.17	440.	1.04	408.	0.97
S5-5/16-2	446.	515.	1.16	498.	1.12	444.	1.00	411.	0.92
S5-5/16-3	440.	511.	1.16	494.	1.12	440.	1.00	408.	0.93
S4-1/4-1	278.	315.	1.13	289.	1.04	256.	0.92	236.	0.85
S4-1/4-2	286.	315.	1.10	290.	1.01	256.	0.90	236.	0.82
S4-1/4-3	311.	317.	1.02	291.	0.94	258.	0.83	237.	0.76
S3.5-5/16-1	350.	359.	1.02	359.	1.02	359.	1.02	350.	1.00
S3.5-5/16-2	366.	359.	0.98	359.	0.98	359.	0.98	351.	0.96
S3.5-5/16-3	350.	360.	1.03	360.	1.03	360.	1.03	352.	1.01
S3-3/8-1	287.	293.	1.02	293.	1.02	293.	1.02	293.	1.02
S3-3/8-2	287.	309.	1.08	309.	1.08	309.	1.08	309.	1.08
S3-3/8-3	288.	309.	1.07	309.	1.07	309.	1.07	309.	1.07
S3-3/8-4	278.	302.	1.09	302.	1.09	302.	1.09	302.	1.09
S3-3/8-5	287.	305.	1.06	305.	1.06	305.	1.06	305.	1.06
S3-3/8-6	289.	309.	1.07	309.	1.07	309.	1.07	309.	1.07
S3-1/4-1	187.	202.	1.08	202.	1.08	198.	1.06	186.	0.99
S3-1/4-2	217.	202.	0.93	202.	0.93	197.	0.91	185.	0.85
S3-1/4-3	208.	200.	0.96	200.	0.96	196.	0.94	184.	0.88

** note : case (I):w=b; (II):w=a+b-t-c; (III):w=a+b-t; (IV):w=a+b
** See Fig. 1.3 for notation:RATIO='Load P as per spec.'/'P Test'

TABLE 5.6b

COMPARISON OF EXPERIMENTAL FAILURE LOADS
AND LOADS CALCULATED ACCORDING TO ASCE MANUAL 52-1988
Strength based on nominal dimensions, PHI=1.00

SPECIMEN	P TEST (kN)	CASE I LOAD (kN)	CASE I RATIO	CASE II LOAD (kN)	CASE II RATIO	CASE III LOAD (kN)	CASE III RATIO	CASE IV LOAD (kN)	CASE IV RATIO
S5-5/16-1	422.	499.	1.18	484.	1.15	436.	1.03	407.	0.97
S5-5/16-2	446.	499.	1.12	484.	1.09	436.	0.98	407.	0.91
S5-5/16-3	440.	499.	1.13	484.	1.10	436.	0.99	407.	0.93
S4-1/4-1	278.	306.	1.10	286.	1.03	259.	0.93	241.	0.87
S4-1/4-2	286.	306.	1.07	286.	1.00	259.	0.90	241.	0.84
S4-1/4-3	311.	306.	0.99	286.	0.92	259.	0.83	241.	0.78
S3.5-5/16-1	350.	306.	0.87	306.	0.87	306.	0.87	306.	0.87
S3.5-5/16-2	366.	306.	0.84	306.	0.84	306.	0.84	306.	0.84
S3.5-5/16-3	350.	306.	0.87	306.	0.87	306.	0.87	306.	0.87
S3-3/8-1	287.	291.	1.01	291.	1.01	291.	1.01	291.	1.01
S3-3/8-2	287.	291.	1.01	291.	1.01	291.	1.01	291.	1.01
S3-3/8-3	288.	291.	1.01	291.	1.01	291.	1.01	291.	1.01
S3-3/8-4	278.	291.	1.05	291.	1.05	291.	1.05	291.	1.05
S3-3/8-5	287.	291.	1.01	291.	1.01	291.	1.01	291.	1.01
S3-3/8-6	289.	291.	1.01	291.	1.01	291.	1.01	291.	1.01
S3-1/4-1	187.	185.	0.99	185.	0.99	185.	0.99	185.	0.99
S3-1/4-2	217.	185.	0.85	185.	0.85	185.	0.85	185.	0.85
S3-1/4-3	208.	185.	0.89	185.	0.89	185.	0.89	185.	0.89

** note : case (I):w=b; (II):w=a+b-t-c; (III):w=a+b-t; (IV):w=a+b
** See Fig. 1.3 for notation;RATIO='Load P as per spec.'/'P Test'

TABLE 5.7a
COMPARISON OF EXPERIMENTAL FAILURE LOADS
AND LOADS CALCULATED ACCORDING TO AISC-LRFD-1986
Strength based on actual dimensions, PHI=1.00

SPECIMEN	P TEST (kN)	CASE I LOAD (kN)	CASE I RATIO	CASE II LOAD (kN)	CASE II RATIO	CASE III LOAD (kN)	CASE III RATIO	CASE IV LOAD (kN)	CASE IV RATIO
S5-5/16-1	422.	374.	0.89	370.	0.88	359.	0.85	352.	0.83
S5-5/16-2	446.	377.	0.84	373.	0.84	362.	0.81	354.	0.79
S5-5/16-3	440.	374.	0.85	370.	0.84	359.	0.82	352.	0.80
S4-1/4-1	278.	235.	0.85	230.	0.83	224.	0.81	220.	0.79
S4-1/4-2	286.	235.	0.82	230.	0.81	224.	0.78	220.	0.77
S4-1/4-3	311.	236.	0.76	231.	0.74	225.	0.72	221.	0.71
S3.5-5/16-1	350.	311.	0.89	311.	0.89	311.	0.89	306.	0.87
S3.5-5/16-2	366.	311.	0.85	311.	0.85	311.	0.85	306.	0.84
S3.5-5/16-3	350.	312.	0.89	312.	0.89	312.	0.89	307.	0.88
S3-3/8-1	287.	257.	0.90	257.	0.90	257.	0.90	257.	0.90
S3-3/8-2	287.	270.	0.94	270.	0.94	270.	0.94	270.	0.94
S3-3/8-3	288.	270.	0.94	270.	0.94	270.	0.94	270.	0.94
S3-3/8-4	278.	265.	0.95	265.	0.95	265.	0.95	265.	0.95
S3-3/8-5	287.	267.	0.93	267.	0.93	267.	0.93	267.	0.93
S3-3/8-6	289.	270.	0.93	270.	0.93	270.	0.93	270.	0.93
S3-1/4-1	187.	173.	0.92	173.	0.92	171.	0.91	169.	0.90
S3-1/4-2	217.	172.	0.79	172.	0.79	170.	0.78	168.	0.78
S3-1/4-3	208.	171.	0.82	171.	0.82	169.	0.81	167.	0.80

** note : case (I):w=b; (II):w=a+b-t-c; (III):w=a+b-t; (IV):w=a+b
** See Fig. 1.3 for notation;RATIO='Load P as per spec.'/'P Test'

TABLE 5.7b
COMPARISON OF EXPERIMENTAL FAILURE LOADS
AND LOADS CALCULATED ACCORDING TO AISC-LRFD-1986
Strength based on nominal dimensions, PHI=1.00

SPECIMEN	P TEST (kN)	CASE I LOAD (kN)	CASE I RATIO	CASE II LOAD (kN)	CASE II RATIO	CASE III LOAD (kN)	CASE III RATIO	CASE IV LOAD (kN)	CASE IV RATIO
S5-5/16-1	422.	366.	0.87	363.	0.86	352.	0.83	345.	0.82
S5-5/16-2	446.	366.	0.82	363.	0.81	352.	0.79	345.	0.77
S5-5/16-3	440.	366.	0.83	363.	0.82	352.	0.80	345.	0.78
S4-1/4-1	278.	228.	0.82	224.	0.81	218.	0.78	214.	0.77
S4-1/4-2	286.	228.	0.80	224.	0.78	218.	0.76	214.	0.75
S4-1/4-3	311.	228.	0.73	224.	0.72	218.	0.70	214.	0.69
S3.5-5/16-1	350.	269.	0.77	269.	0.77	269.	0.77	269.	0.77
S3.5-5/16-2	366.	269.	0.74	269.	0.74	269.	0.74	269.	0.74
S3.5-5/16-3	350.	269.	0.77	269.	0.77	269.	0.77	269.	0.77
S3-3/8-1	287.	249.	0.87	249.	0.87	249.	0.87	249.	0.87
S3-3/8-2	287.	249.	0.87	249.	0.87	249.	0.87	249.	0.87
S3-3/8-3	288.	249.	0.87	249.	0.87	249.	0.87	249.	0.87
S3-3/8-4	278.	249.	0.90	249.	0.90	249.	0.90	249.	0.90
S3-3/8-5	287.	249.	0.87	249.	0.87	249.	0.87	249.	0.87
S3-3/8-6	289.	249.	0.86	249.	0.86	249.	0.86	249.	0.86
S3-1/4-1	187.	159.	0.85	159.	0.85	159.	0.85	158.	0.84
S3-1/4-2	217.	159.	0.73	159.	0.73	159.	0.73	158.	0.73
S3-1/4-3	208.	159.	0.76	159.	0.76	159.	0.76	158.	0.76

** note : case (I):w=b; (II):w=a+b-t-c; (III):w=a+b-t; (IV):w=a+b
** See Fig. 1.3 for notation;RATIO='Load P as per spec.'/'P Test'

TABLE 5.7c
COMPARISON OF EXPERIMENTAL FAILURE LOADS
AND LOADS CALCULATED ACCORDING TO AISC-LRFD-1986
Strength based on actual dimensions, PHI=0.85

SPECIMEN	P TEST (kN)	CASE I LOAD (kN)	CASE I RATIO	CASE II LOAD (kN)	CASE II RATIO	CASE III LOAD (kN)	CASE III RATIO	CASE IV LOAD (kN)	CASE IV RATIO
S5-5/16-1	422.	318.	0.75	315.	0.75	305.	0.72	299.	0.71
S5-5/16-2	446.	320.	0.72	317.	0.71	307.	0.69	301.	0.68
S5-5/16-3	440.	318.	0.72	315.	0.72	305.	0.69	299.	0.68
S4-1/4-1	278.	200.	0.72	196.	0.70	190.	0.68	187.	0.67
S4-1/4-2	286.	200.	0.70	196.	0.68	190.	0.67	187.	0.65
S4-1/4-3	311.	201.	0.64	197.	0.63	191.	0.61	187.	0.60
S3.5-5/16-1	350.	264.	0.75	264.	0.75	264.	0.75	260.	0.74
S3.5-5/16-2	366.	265.	0.72	265.	0.72	265.	0.72	260.	0.71
S3.5-5/16-3	350.	265.	0.76	265.	0.76	265.	0.76	261.	0.75
S3-3/8-1	287.	219.	0.76	219.	0.76	219.	0.76	219.	0.76
S3-3/8-2	287.	229.	0.80	229.	0.80	229.	0.80	229.	0.80
S3-3/8-3	288.	229.	0.80	229.	0.80	229.	0.80	229.	0.80
S3-3/8-4	278.	225.	0.81	225.	0.81	225.	0.81	225.	0.81
S3-3/8-5	287.	227.	0.79	227.	0.79	227.	0.79	227.	0.79
S3-3/8-6	289.	229.	0.79	229.	0.79	229.	0.79	229.	0.79
S3-1/4-1	187.	147.	0.78	147.	0.78	145.	0.78	143.	0.77
S3-1/4-2	217.	146.	0.67	146.	0.67	145.	0.67	143.	0.66
S3-1/4-3	208.	145.	0.70	145.	0.70	144.	0.69	142.	0.68

** note : case (I):w=b; (II):w=a+b-t-c; (III):w=a+b-t; (IV):w=a+b
** See Fig. 1.3 for notation;RATIO='Load P as per spec.'/'P Test'

TABLE 5.7d
COMPARISON OF EXPERIMENTAL FAILURE LOADS
AND LOADS CALCULATED ACCORDING TO AISC-LRFD-1986
Strength based on nominal dimensions, PHI=0.85

SPECIMEN	P TEST (kN)	CASE I LOAD (kN)	CASE I RATIO	CASE II LOAD (kN)	CASE II RATIO	CASE III LOAD (kN)	CASE III RATIO	CASE IV LOAD (kN)	CASE IV RATIO
S5-5/16-1	422.	311.	0.74	308.	0.73	299.	0.71	293.	0.69
S5-5/16-2	446.	311.	0.70	308.	0.69	299.	0.67	293.	0.66
S5-5/16-3	440.	311.	0.71	308.	0.70	299.	0.68	293.	0.67
S4-1/4-1	278.	194.	0.70	190.	0.68	185.	0.67	182.	0.65
S4-1/4-2	286.	194.	0.68	190.	0.67	185.	0.65	182.	0.64
S4-1/4-3	311.	194.	0.62	190.	0.61	185.	0.60	182.	0.58
S3.5-5/16-1	350.	229.	0.65	229.	0.65	229.	0.65	229.	0.65
S3.5-5/16-2	366.	229.	0.63	229.	0.63	229.	0.63	229.	0.63
S3.5-5/16-3	350.	229.	0.65	229.	0.65	229.	0.65	229.	0.65
S3-3/8-1	287.	212.	0.74	212.	0.74	212.	0.74	212.	0.74
S3-3/8-2	287.	212.	0.74	212.	0.74	212.	0.74	212.	0.74
S3-3/8-3	288.	212.	0.74	212.	0.74	212.	0.74	212.	0.74
S3-3/8-4	278.	212.	0.76	212.	0.76	212.	0.76	212.	0.76
S3-3/8-5	287.	212.	0.74	212.	0.74	212.	0.74	212.	0.74
S3-3/8-6	289.	212.	0.73	212.	0.73	212.	0.73	212.	0.73
S3-1/4-1	187.	135.	0.72	135.	0.72	135.	0.72	134.	0.72
S3-1/4-2	217.	135.	0.62	135.	0.62	135.	0.62	134.	0.62
S3-1/4-3	208.	135.	0.65	135.	0.65	135.	0.65	134.	0.65

** note : case (I):w=b; (II):w=a+b-t-c; (III):w=a+b-t; (IV):w=a+b
** See Fig. 1.3 for notation;RATIO='Load P as per spec.'/'P Test'

TABLE 5.8a
COMPARISON OF EXPERIMENTAL FAILURE LOADS
AND LOADS CALCULATED ACCORDING TO BS 5950:PART 1:1995
Strength based on actual dimensions

SPECIMEN	P TEST (kN)	CASE I LOAD (kN)	CASE I RATIO	CASE II LOAD (kN)	CASE II RATIO	CASE III LOAD (kN)	CASE III RATIO	CASE IV LOAD (kN)	CASE IV RATIO
S5-5/16-1	422.	385.	0.91	374.	0.89	361.	0.85	361.	0.85
S5-5/16-2	446.	389.	0.87	378.	0.85	364.	0.82	364.	0.82
S5-5/16-3	440.	385.	0.88	374.	0.85	360.	0.82	360.	0.82
S4-1/4-1	278.	237.	0.85	208.	0.75	202.	0.73	202.	0.73
S4-1/4-2	286.	237.	0.83	208.	0.73	202.	0.71	202.	0.71
S4-1/4-3	311.	238.	0.77	209.	0.67	203.	0.65	203.	0.65
S3.5-5/16-1	350.	274.	0.78	274.	0.78	257.	0.74	242.	0.69
S3.5-5/16-2	366.	274.	0.75	274.	0.75	258.	0.70	243.	0.66
S3.5-5/16-3	350.	275.	0.79	275.	0.79	258.	0.74	243.	0.69
S3-3/8-1	287.	223.	0.78	223.	0.78	223.	0.78	223.	0.78
S3-3/8-2	287.	227.	0.79	227.	0.79	227.	0.79	227.	0.79
S3-3/8-3	288.	227.	0.79	227.	0.79	227.	0.79	227.	0.79
S3-3/8-4	278.	225.	0.81	225.	0.81	225.	0.81	225.	0.81
S3-3/8-5	287.	226.	0.79	226.	0.79	226.	0.79	226.	0.79
S3-3/8-6	289.	227.	0.78	227.	0.78	227.	0.78	227.	0.78
S3-1/4-1	187.	147.	0.79	147.	0.79	134.	0.72	132.	0.70
S3-1/4-2	217.	147.	0.6[illegible]	147.	0.68	134.	0.62	131.	0.61
S3-1/4-3	208.	147.	0.70	147.	0.70	134.	0.64	131.	0.63

** note : case (I):w=b; (II):w=a+b-t-c; (III):w=a+b-t; (IV):w=a+b
** See Fig. 1.3 for notation;RATIO='Load P as per spec.'/'P Test'

TABLE 5.8b
COMPARISON OF EXPERIMENTAL FAILURE LOADS
AND LOADS CALCULATED ACCORDING TO BS 5950:PART 1:1985
Strength based on nominal dimensions

SPECIMEN	P TEST (kN)	CASE I LOAD (kN)	CASE I RATIO	CASE II LOAD (kN)	CASE II RATIO	CASE III LOAD (kN)	CASE III RATIO	CASE IV LOAD (kN)	CASE IV RATIO
S5-5/16-1	422.	383.	0.91	369.	0.87	369.	0.87	369.	0.87
S5-5/16-2	446.	383.	0.86	369.	0.83	369.	0.83	369.	0.83
S5-5/16-3	440.	383.	0.87	369.	0.84	369.	0.84	369.	0.84
S4-1/4-1	278.	220.	0.79	207.	0.75	207.	0.75	207.	0.75
S4-1/4-2	286.	220.	0.77	207.	0.73	207.	0.73	207.	0.73
S4-1/4-3	311.	220.	0.71	207.	0.67	207.	0.67	207.	0.67
S3.5-5/16-1	350.	232.	0.66	232.	0.66	232.	0.66	232.	0.66
S3.5-5/16-2	366.	232.	0.63	232.	0.63	232.	0.63	232.	0.63
S3.5-5/16-3	350.	232.	0.66	232.	0.66	232.	0.66	232.	0.66
S3-3/8-1	287.	215.	0.75	215.	0.75	215.	0.75	215.	0.75
S3-3/8-2	287.	215.	0.75	215.	0.75	215.	0.75	215.	0.75
S3-3/8-3	288.	215.	0.75	215.	0.75	215.	0.75	215.	0.75
S3-3/8-4	278.	215.	0.77	215.	0.77	215.	0.77	215.	0.77
S3-3/8-5	287.	215.	0.75	215.	0.75	215.	0.75	215.	0.75
S3-3/8-6	289.	215.	0.74	215.	0.74	215.	0.74	215.	0.74
S3-1/4-1	187.	133.	0.71	133.	0.71	133.	0.71	125.	0.67
S3-1/4-2	217.	133.	0.61	133.	0.61	133.	0.61	125.	0.58
S3-1/4-3	208.	133.	0.64	133.	0.64	133.	0.64	125.	0.60

** note : case (I):w=b; (II):w=a+b-t-c; (III):w=a+b-t; (IV):w=a+b
** See Fig. 1.3 for notation;RATIO='Load P as per spec.'/'P Test'

TABLE 5.9a
COMPARISON OF EXPERIMENTAL FAILURE LOADS
AND LOADS CALCULATED ACCORDING TO ECCS - 1985
Strength based on actual dimensions

SPECIMEN	P TEST (kN)	CASE I LOAD (kN)	CASE I RATIO	CASE II LOAD (kN)	CASE II RATIO	CASE III LOAD (kN)	CASE III RATIO	CASE IV LOAD (kN)	CASE IV RATIO
S5-5/16-1	422.	574.	1.36	574.	1.36	546.	1.29	505.	1.20
S5-5/16-2	446.	582.	1.30	582.	1.30	551.	1.24	510.	1.14
S5-5/16-3	440.	574.	1.30	574.	1.30	546.	1.24	505.	1.15
S4-1/4-1	278.	360.	1.30	360.	1.30	323.	1.16	297.	1.07
S4-1/4-2	286.	360.	1.26	360.	1.26	324.	1.13	298.	1.04
S4-1/4-3	311.	362.	1.16	362.	1.16	325.	1.04	299.	0.96
S3.5-5/16-1	350.	337.	0.96	337.	0.96	337.	0.96	337.	0.96
S3.5-5/16-2	366.	338.	0.92	338.	0.92	338.	0.92	338.	0.92
S3.5-5/16-3	350.	339.	0.97	339.	0.97	339.	0.97	339.	0.97
S3-3/8-1	287.	261.	0.91	261.	0.91	261.	0.91	261.	0.91
S3-3/8-2	287.	272.	0.95	272.	0.95	272.	0.95	272.	0.95
S3-3/8-3	288.	272.	0.94	272.	0.94	272.	0.94	272.	0.94
S3-3/8-4	278.	267.	0.96	267.	0.96	267.	0.96	267.	0.96
S3-3/8-5	287.	271.	0.94	271.	0.94	271.	0.94	271.	0.94
S3-3/8-6	289.	272.	0.94	272.	0.94	272.	0.94	272.	0.94
S3-1/4-1	187.	179.	0.95	179.	0.95	179.	0.95	179.	0.95
S3-1/4-2	217.	178.	0.82	178.	0.82	178.	0.82	178.	0.82
S3-1/4-3	208.	175.	0.84	175.	0.84	175.	0.84	175.	0.84

** note : case (I):w=b; (II):w=a+b-t-c; (III):w=a+b-t; (IV):w=a+b
** See Fig. 1.3 for notation;RATIO='Load P as per spec.'/'P Test'

TABLE 5.9b
COMPARISON OF EXPERIMENTAL FAILURE LOADS
AND LOADS CALCULATED ACCORDING TO ECCS - 1985
Strength based on nominal dimensions

SPECIMEN	P TEST (kN)	CASE I LOAD (kN)	CASE I RATIO	CASE II LOAD (kN)	CASE II RATIO	CASE III LOAD (kN)	CASE III RATIO	CASE IV LOAD (kN)	CASE IV RATIO
S5-5/16-1	422.	537.	1.27	537.	1.27	537.	1.27	501.	1.19
S5-5/16-2	446.	537.	1.20	537.	1.20	537.	1.20	501.	1.12
S5-5/16-3	440.	537.	1.22	537.	1.22	537.	1.22	501.	1.14
S4-1/4-1	278.	318.	1.14	318.	1.14	318.	1.14	297.	1.07
S4-1/4-2	286.	318.	1.11	318.	1.11	318.	1.11	297.	1.04
S4-1/4-3	311.	318.	1.02	31[illegible]	1.02	318.	1.02	297.	0.95
S3.5-5/16-1	350.	298.	0.85	298.	0.85	298.	0.85	298.	0.85
S3.5-5/16-2	366.	298.	0.81	298.	0.81	298.	0.81	298.	0.81
S3.5-5/16-3	350.	298.	0.85	298.	0.85	298.	0.85	298.	0.85
S3-3/8-1	287.	253.	0.88	253.	0.88	253.	0.88	253.	0.88
S3-3/8-2	287.	253.	0.88	253.	0.88	253.	0.88	253.	0.88
S3-3/8-3	288.	253.	0.88	253.	0.88	253.	0.88	253.	0.88
S3-3/8-4	278.	253.	0.91	253.	0.91	253.	0.91	253.	0.91
S3-3/8-5	287.	253.	0.88	253.	0.88	253.	0.88	253.	0.88
S3-3/8-6	289.	253.	0.88	253.	0.88	253.	0.88	253.	0.88
S3-1/4-1	187.	169.	0.90	[illegible].	0.90	169.	0.90	169.	0.90
S3-1/4-2	217.	169.	0.78	169.	0.78	169.	0.78	169.	0.78
S3-1/4-3	208.	169.	0.81	169.	0.81	169.	0.81	169.	0.81

** note : case (I):w=b; (II):w=a+b-t-c; (III):w=a+b-t; (IV):w=a+b
** See Fig. 1.3 for notation;RATIO='Load P as per spec.'/'P Test'

FIGURES

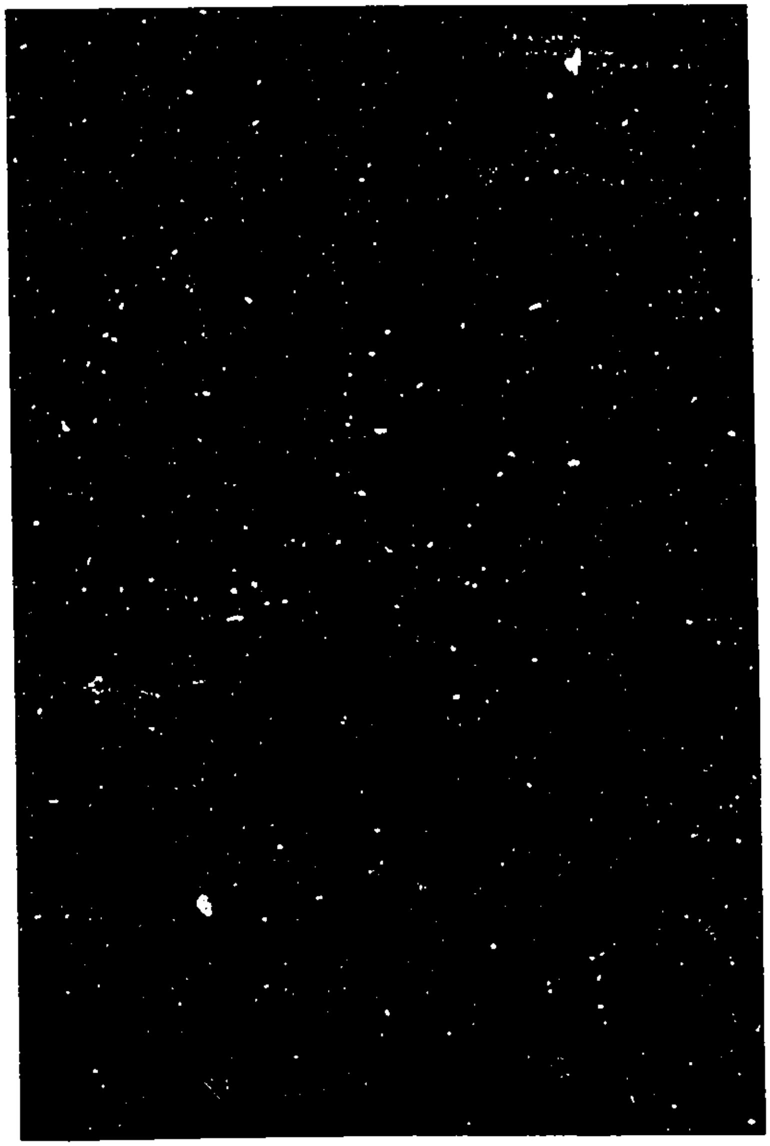


Fig.1.1
300m-high Guyed Television Mast
at Barrie, Ontario

Fig.1.2

Typical Self-supporting Antenna Tower

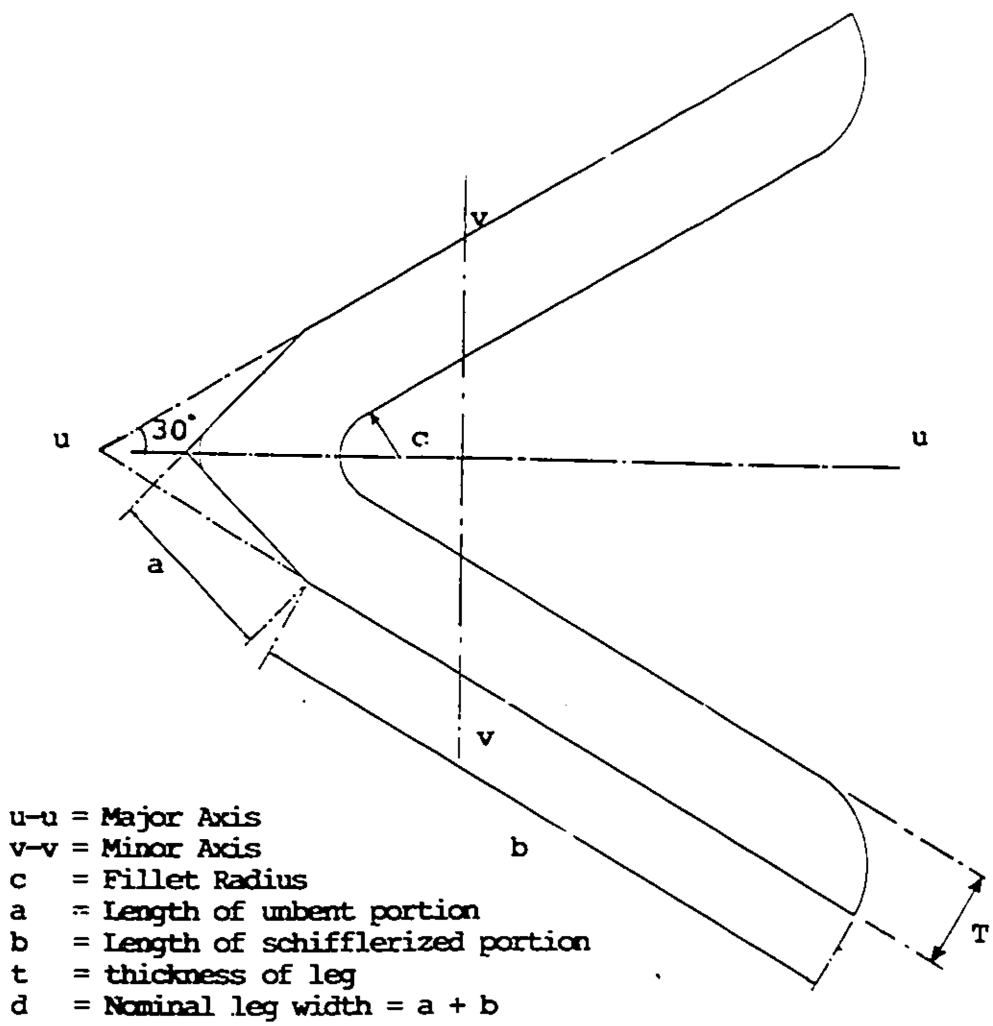


Fig.1.3

Typical Cross-section of a Schifflerized Angle

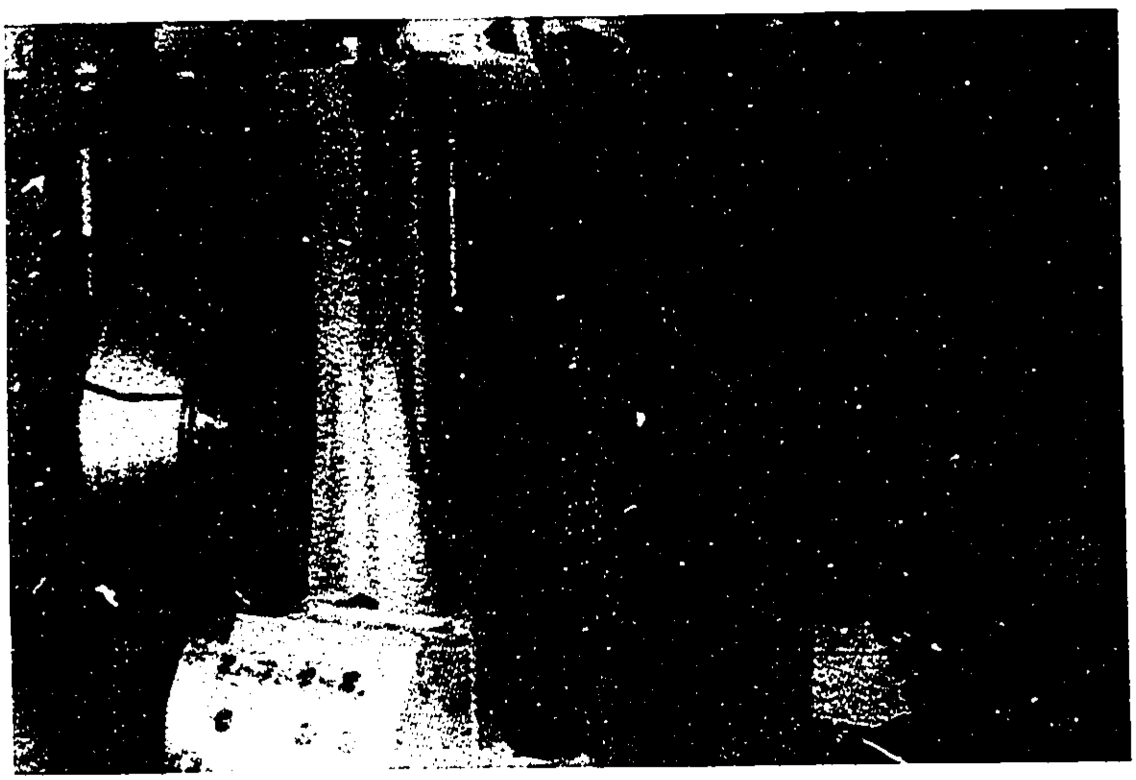


Fig.1.4

Rollers used for Schifflerization

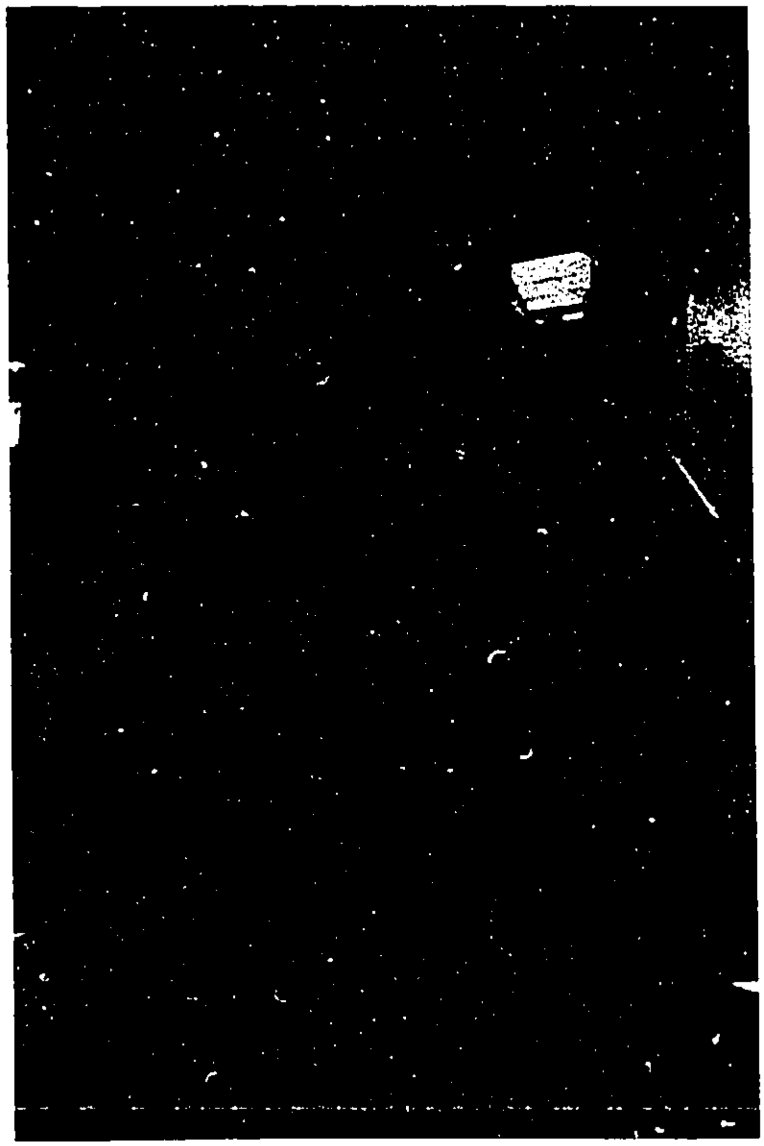


Fig.1.5

Brake-Press used for Schifflerizaton

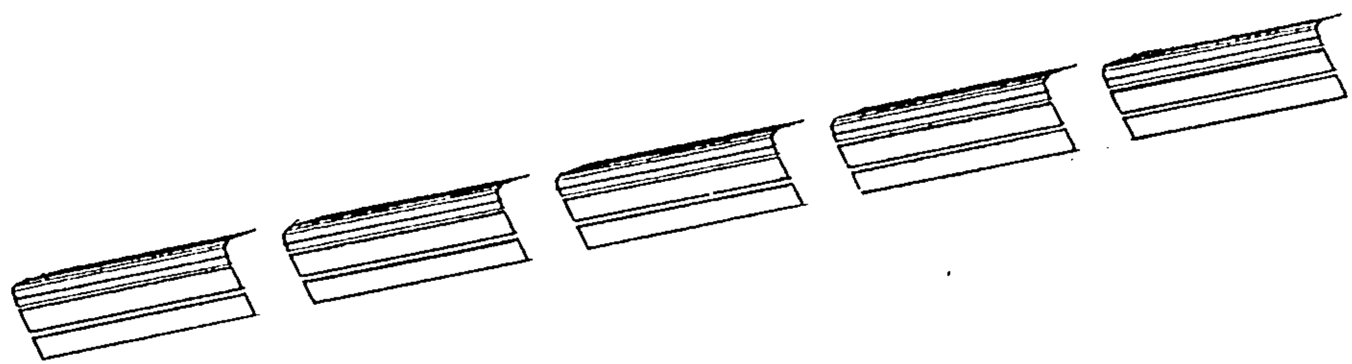


Fig.3.1

Finite Element Discretization of Schifflerized Angle using Rectangular Eight-Node Shell Elements

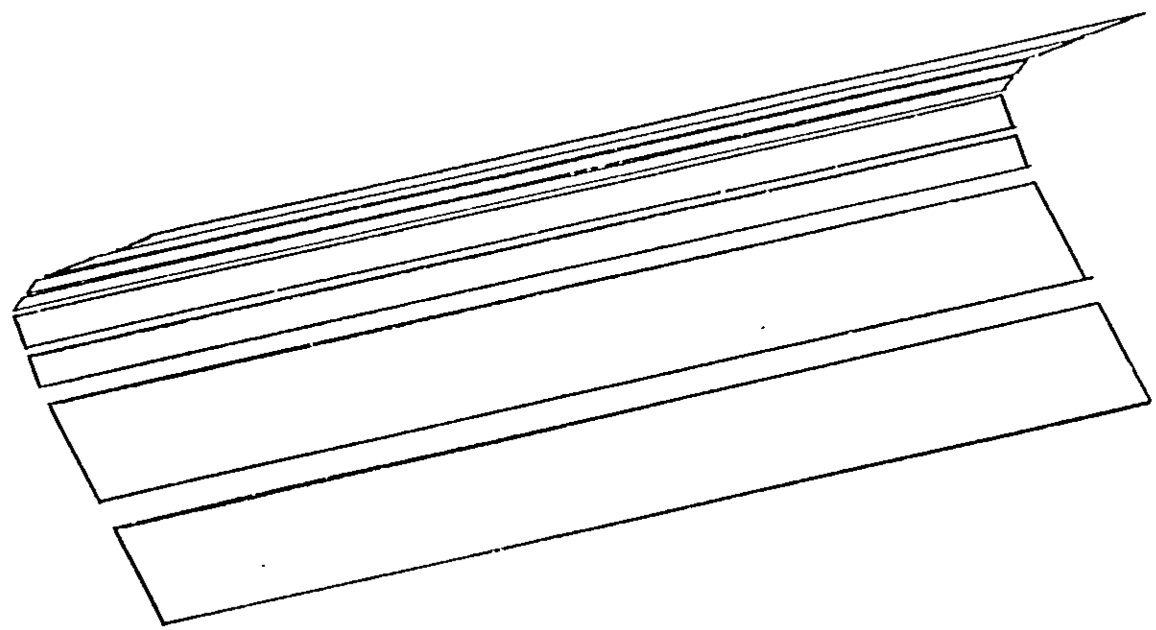


Fig.3.2

Enlarged View of a Single Segment of the Finite Element Model for Schifflerized Angle

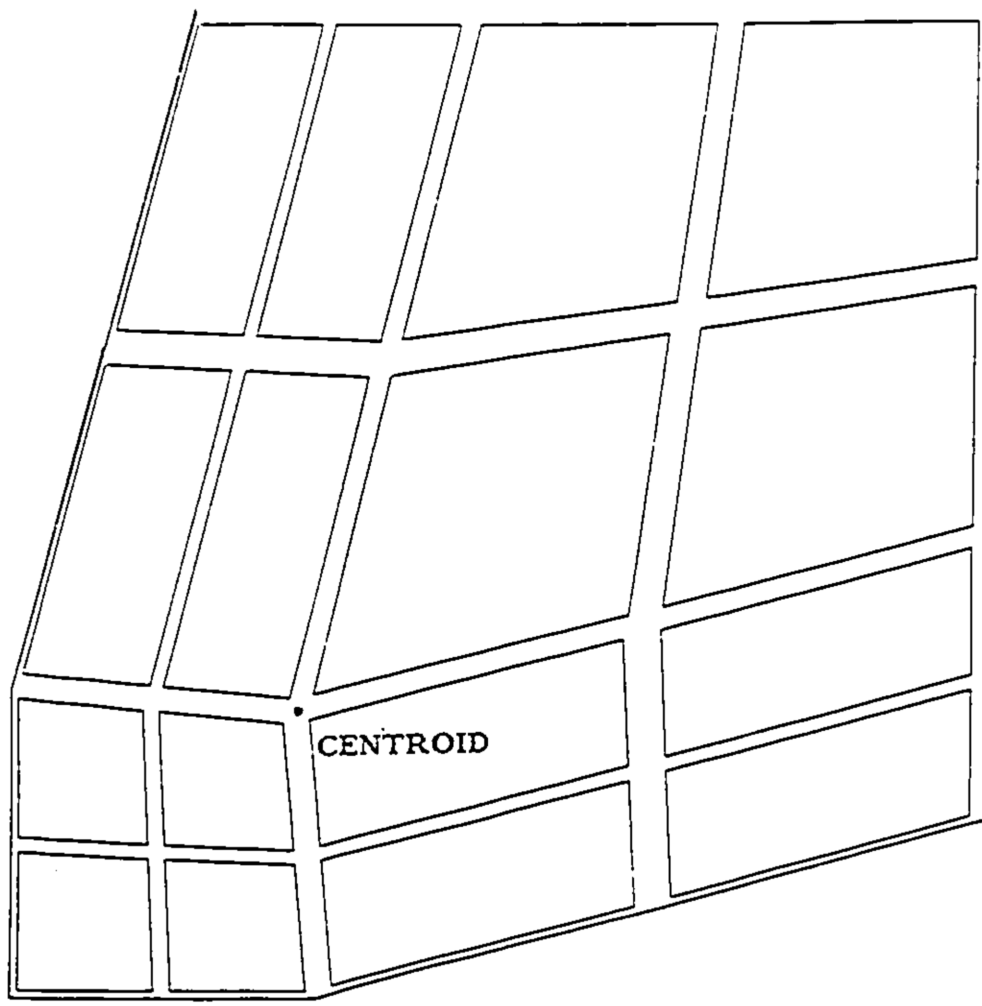


Fig.3.3
Finite Element Discretization of the End Plate
using Eight-Node Shell Elements

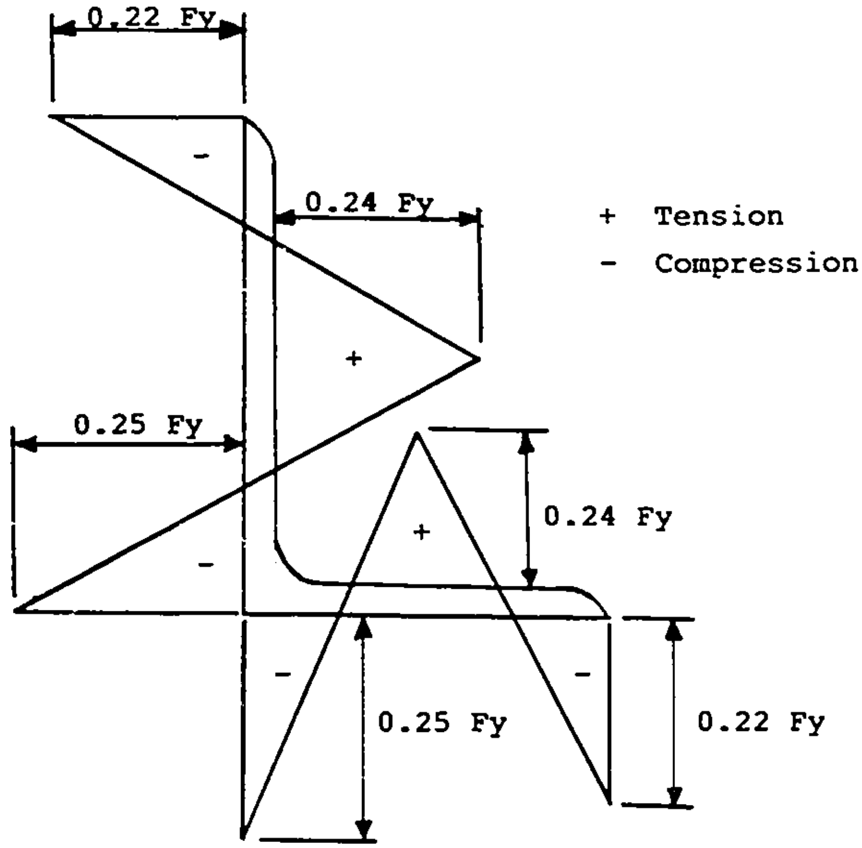


Fig.3.4
Residual Stress distribution over the Cross-section of a Hot-Rolled Angle [ECCS]

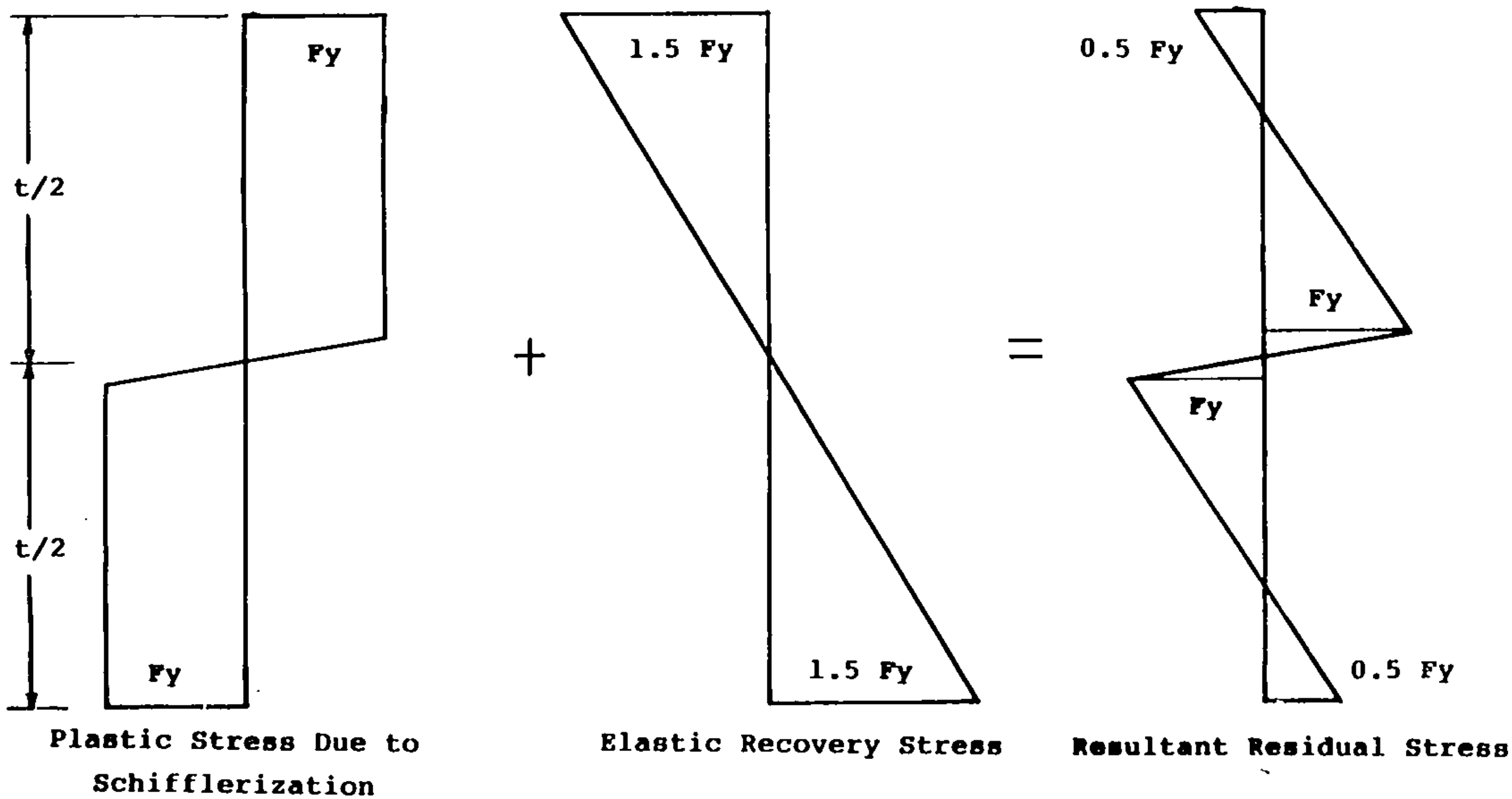


Fig.3.5
Residual Stress distribution through the
thickness of a Schifflerized Angle Leg

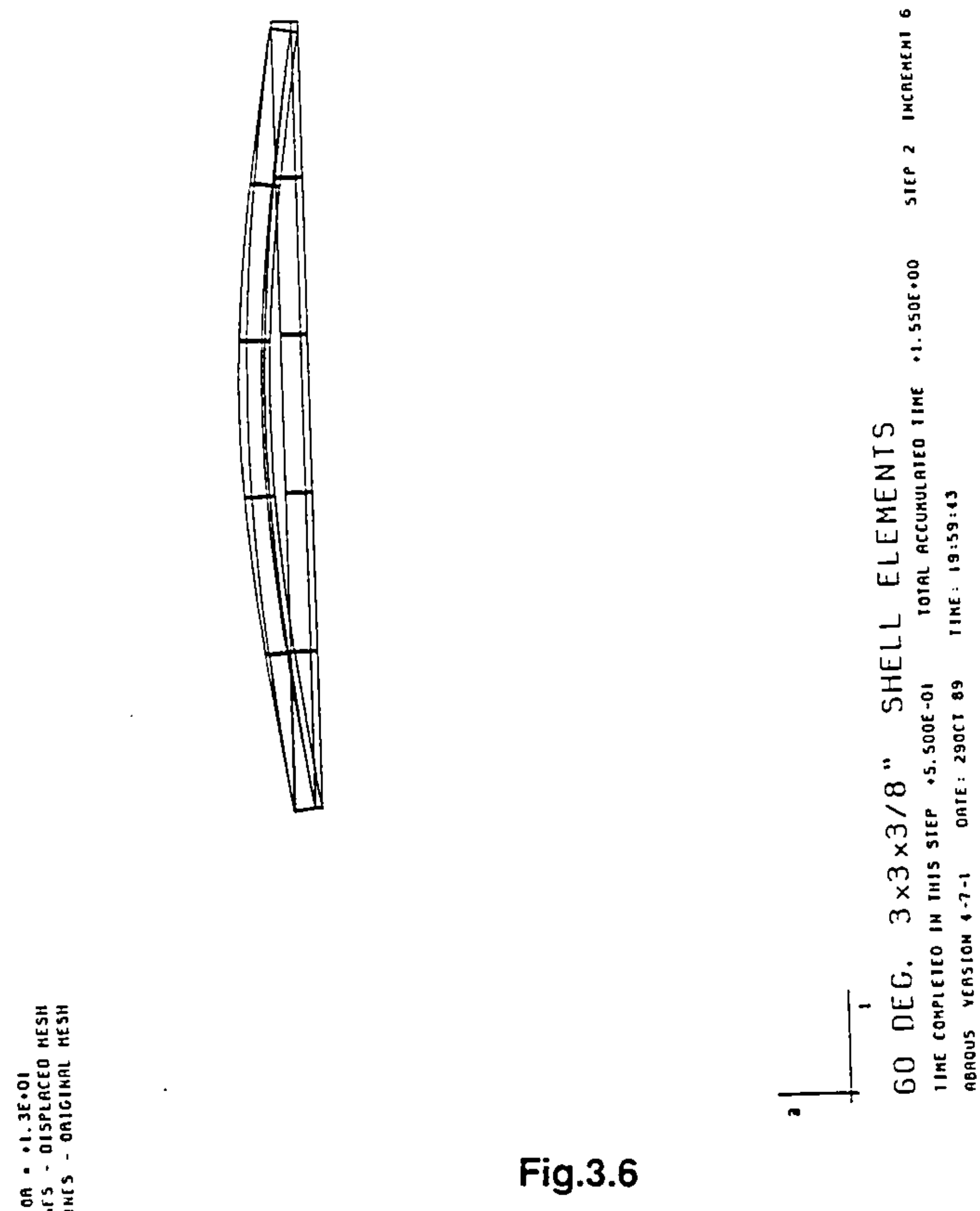


Fig.3.6

Deformed Shape in Flexural Buckling Mode

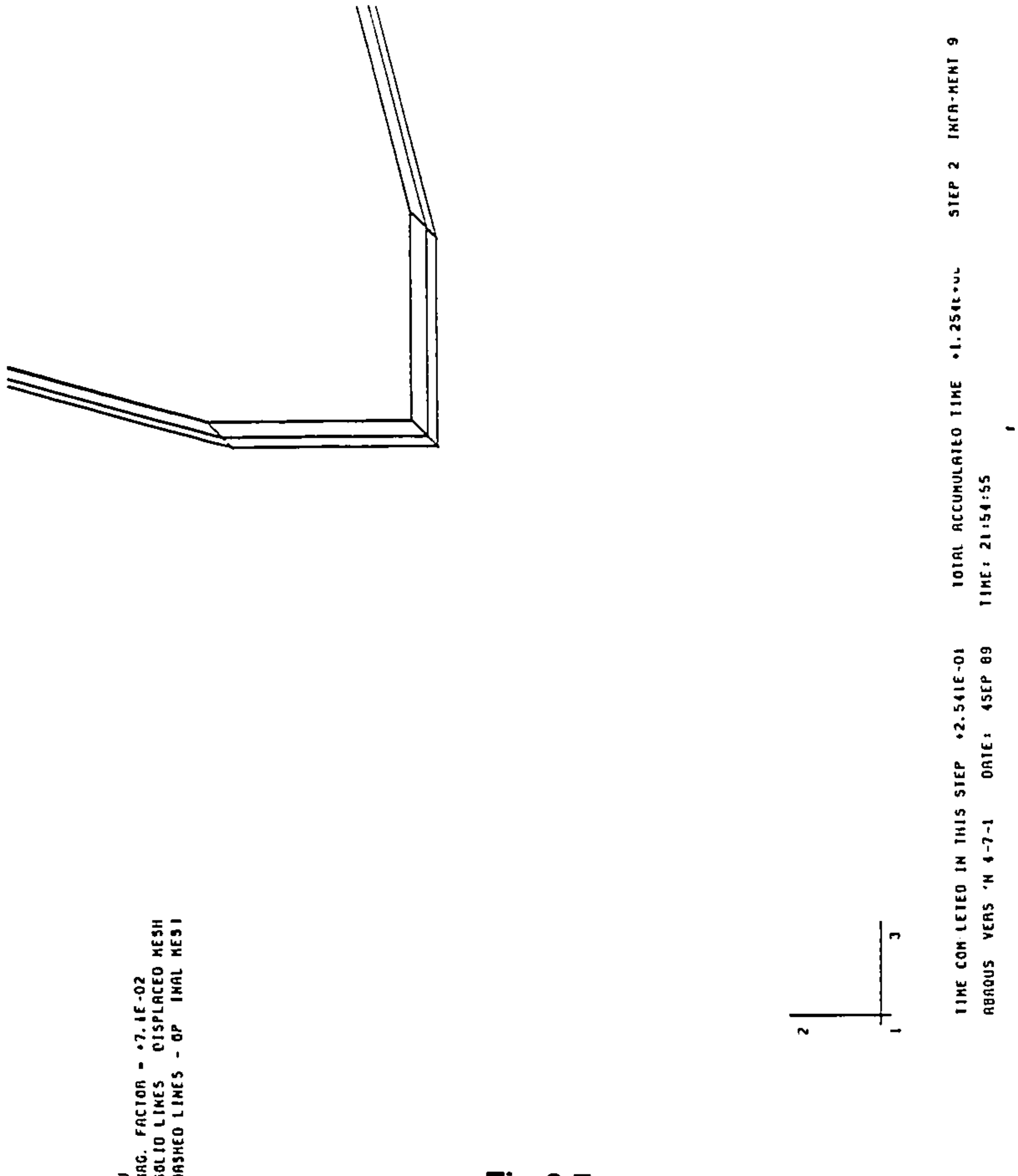


Fig.3.7

Deformed Shape in Flexural Buckling Mode showing End View

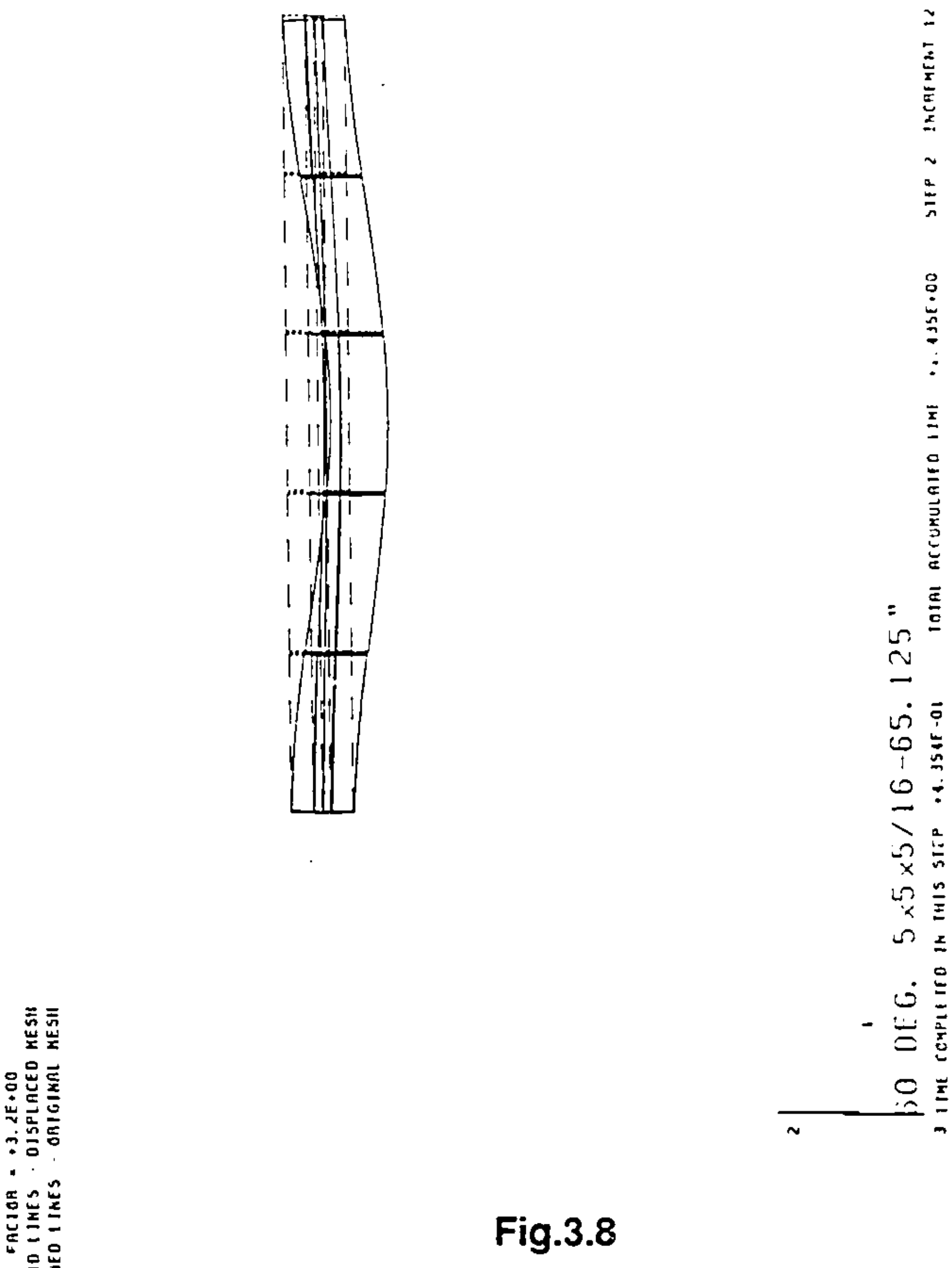


Fig.3.8

Deformed Shape in Torsional-Flexural Buckling Mode showing Major Axis Buckling

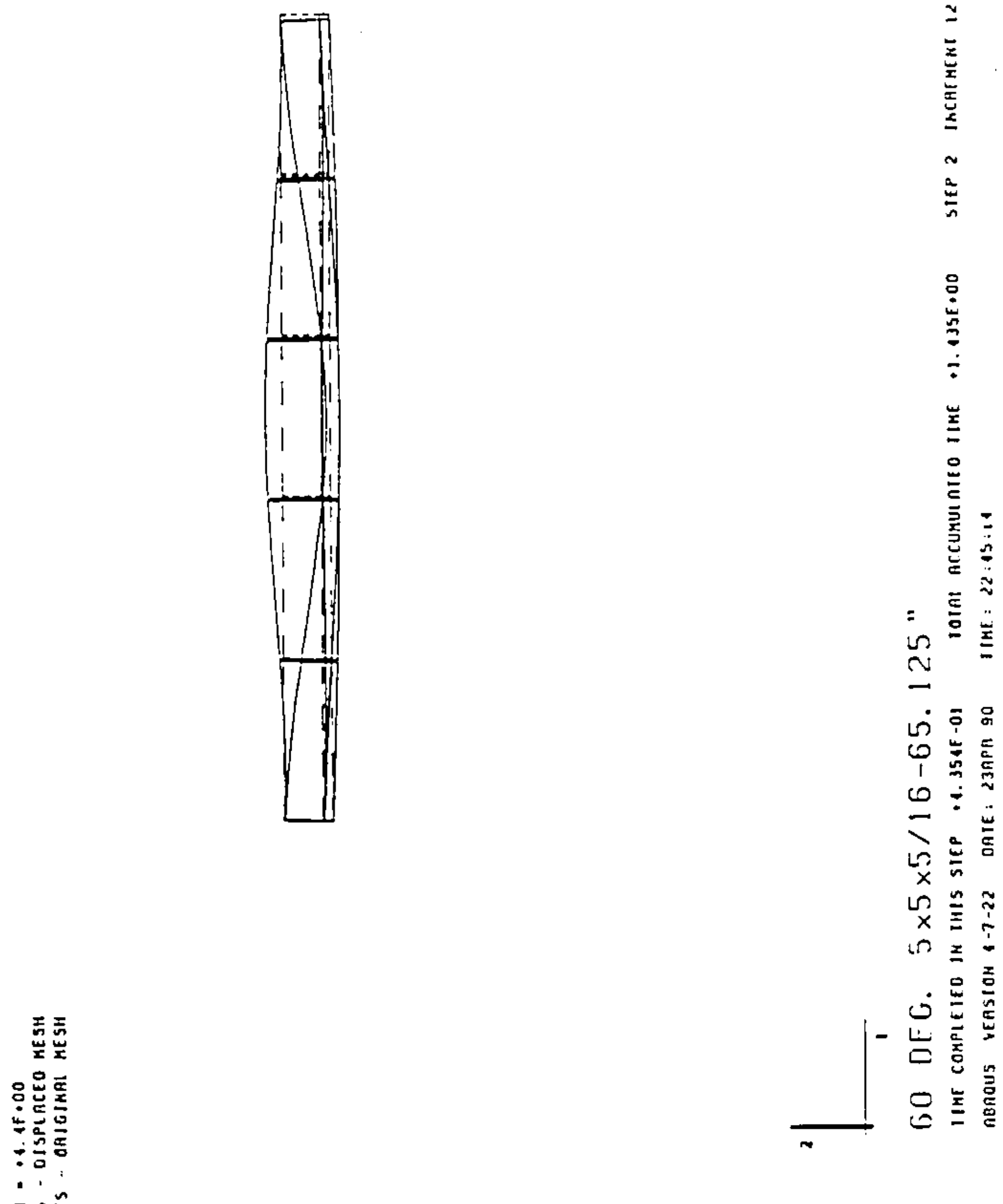


Fig.3.9

Deformed Shape in Torsional-Flexural Buckling Mode showing Twist of the angle

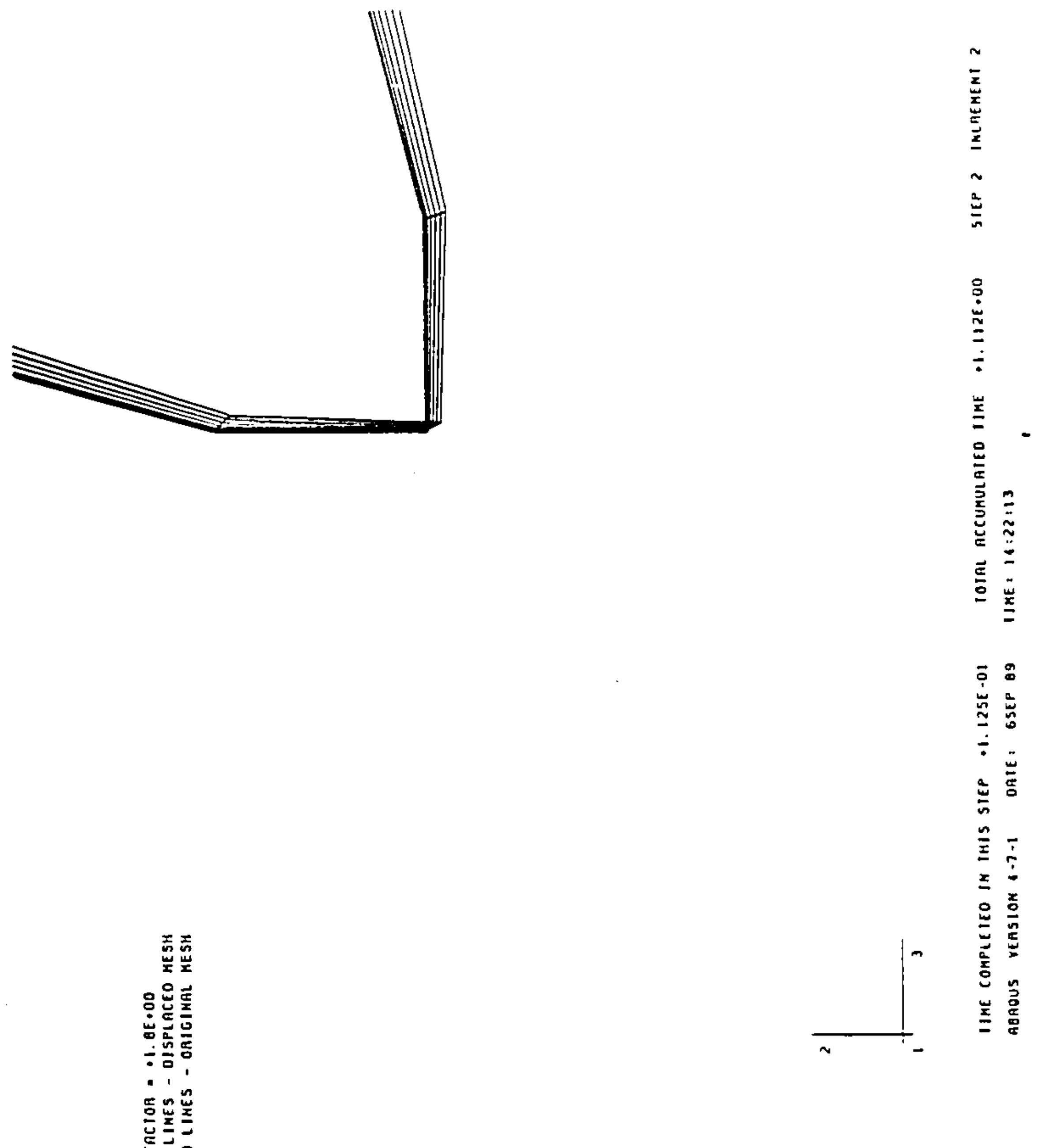
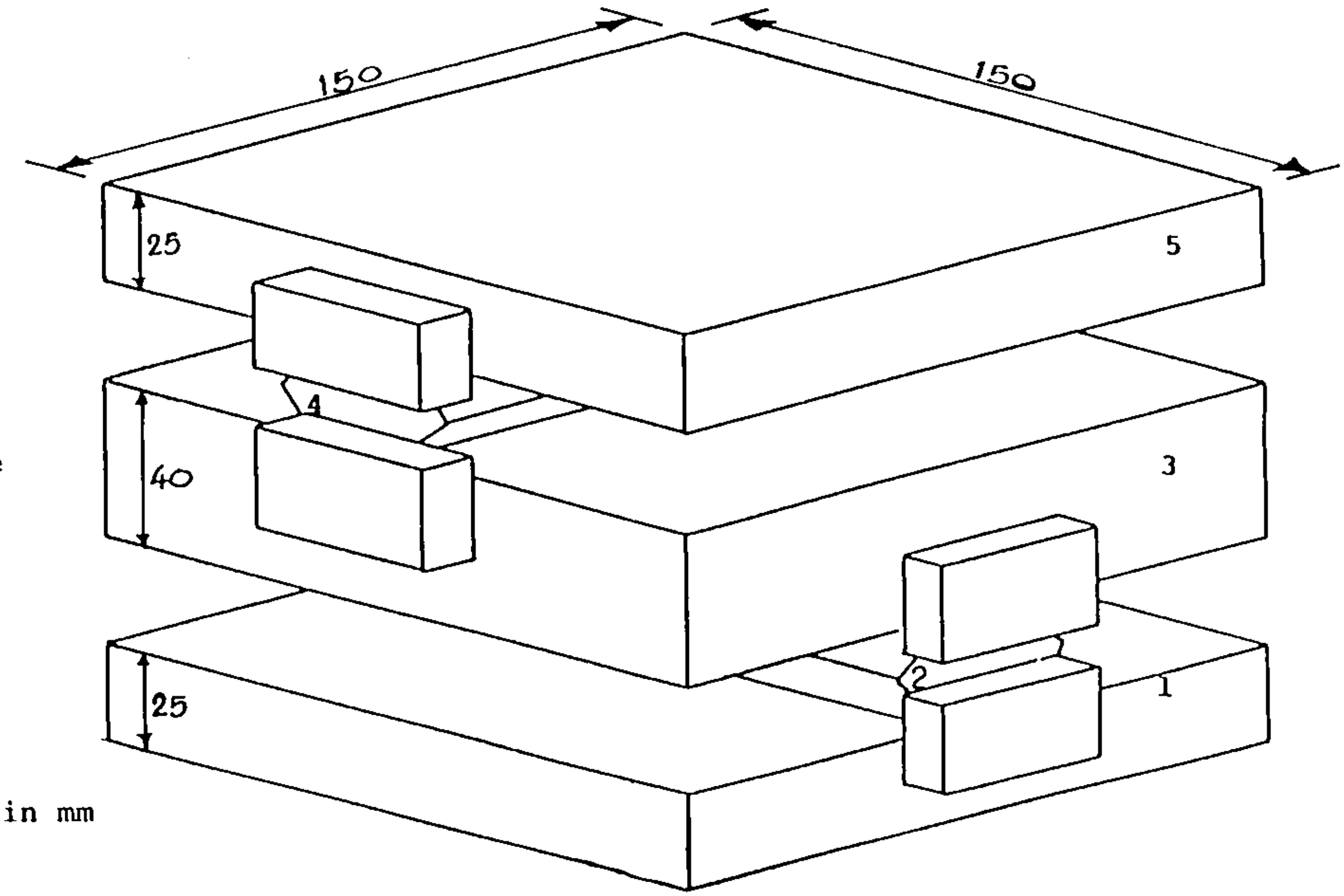


Fig.3.10

Deformed Shape in Torsional-Flexural Buckling Mode showing End View



1 Bottom Plate
2 Bottom Knife Edge
3 Centre Plate
4 Top Knife Edge
5 Top Plate

* All dimensions in mm

Fig.4.1

End Plate Assembly for Hinged End Condition

Fig.4.2
Movable Blocking Plates to keep the Test Specimens in Alignment

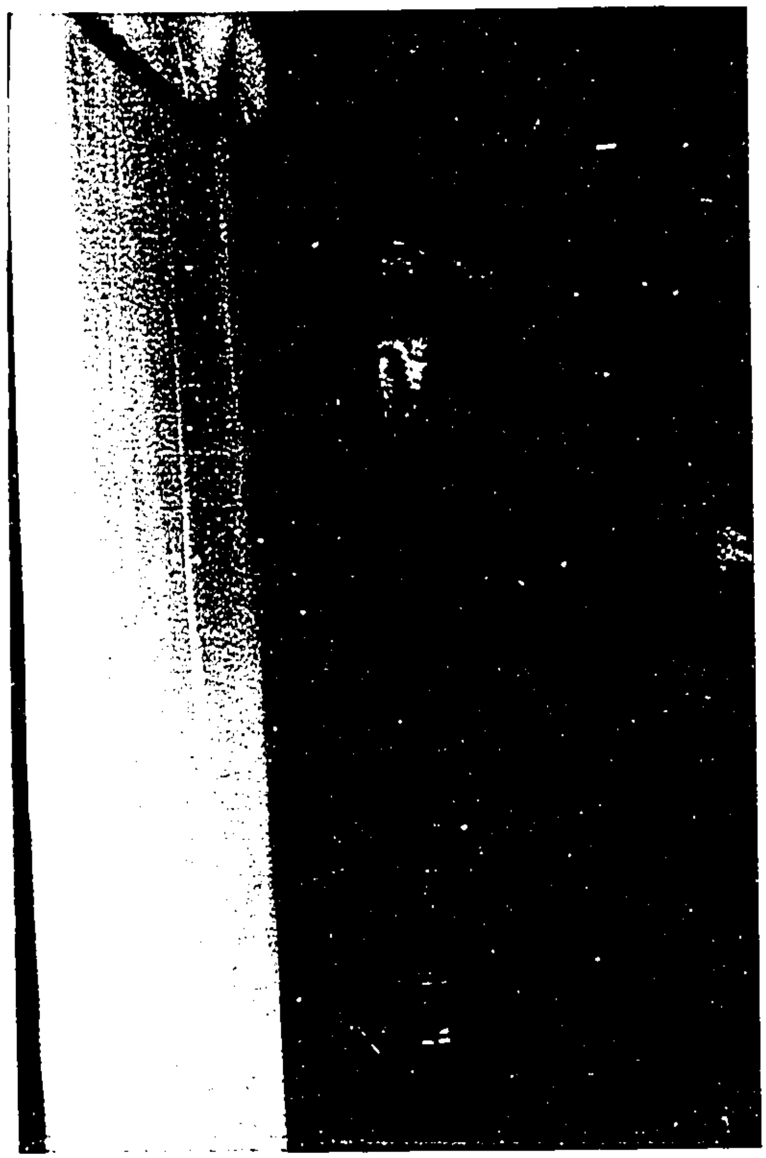
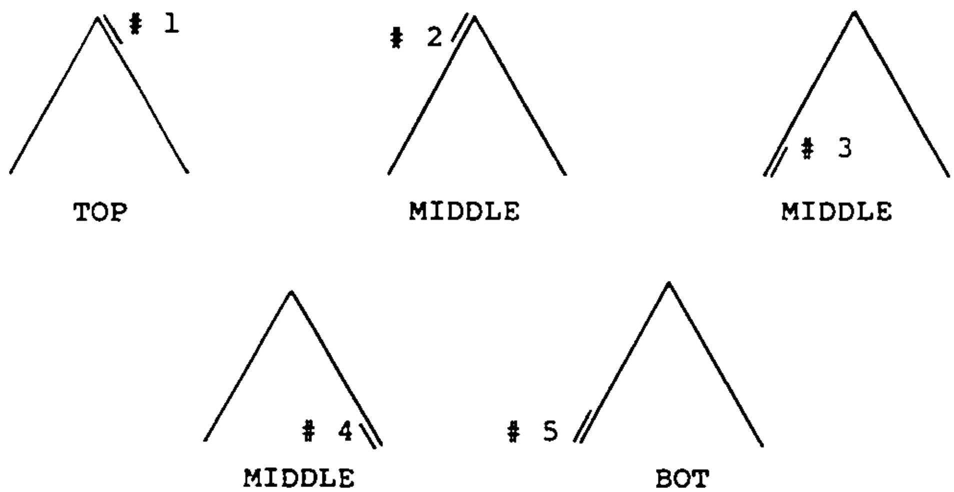
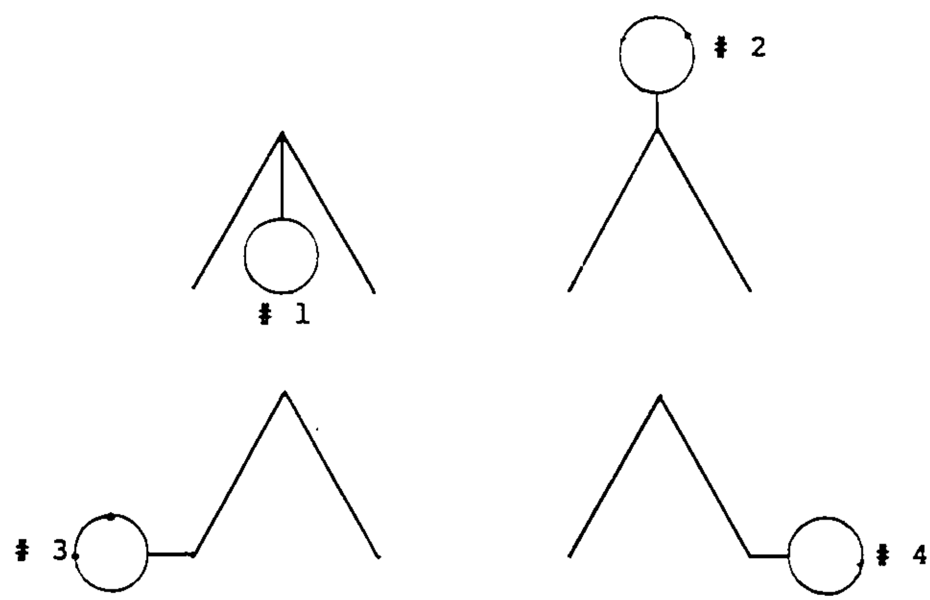


Fig.4.3
Set-up showing a Test Specimen with
Electrical Strain Gauges attached



Location of Strain Gauges along Member Height



Location of Dial Gauges at Mid-height

Fig.4.4

Location of Strain Gauges and Dial Gauges

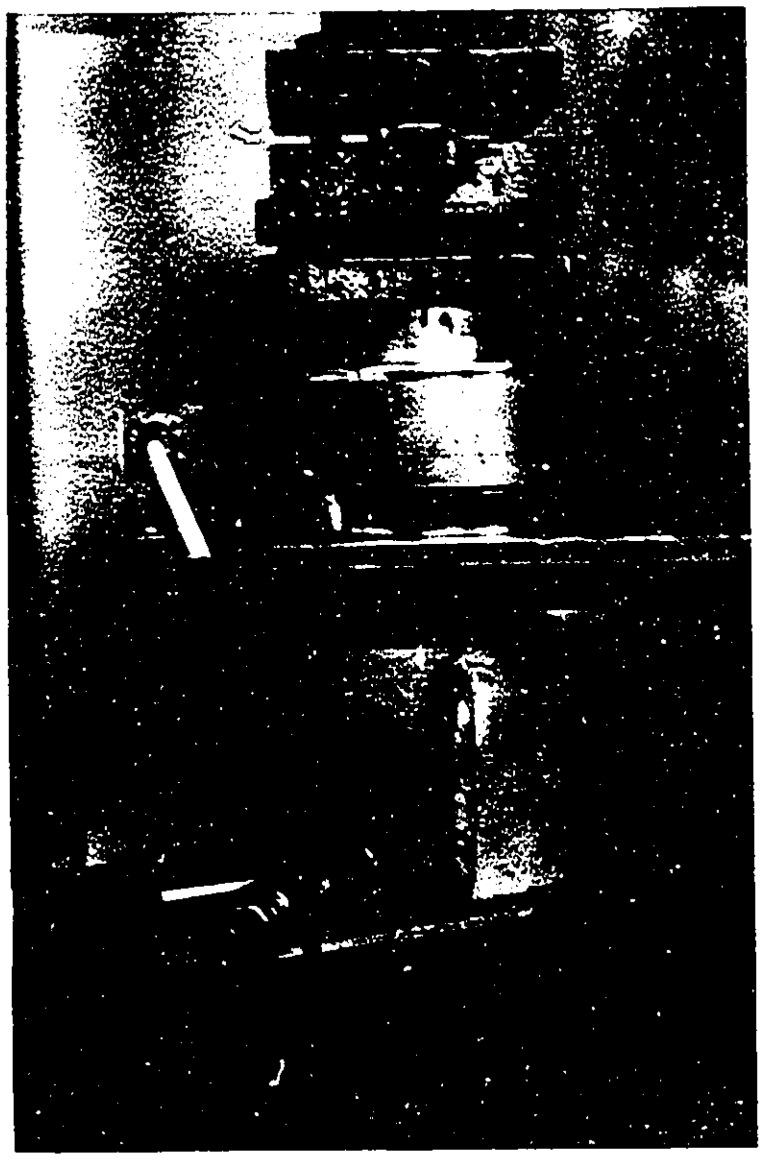


Fig.4.5

Hydraulic Jack, Load Cell and End-Plate Assembly

Fig.4.6

Test Set-up for the Schifflerized Angle showing Pump, Strain and Load Indicators and Dial Gauges

Fig.4.7a
Specimen S4 - 1/4 - 1 showing
Torsional-Flexural Buckling

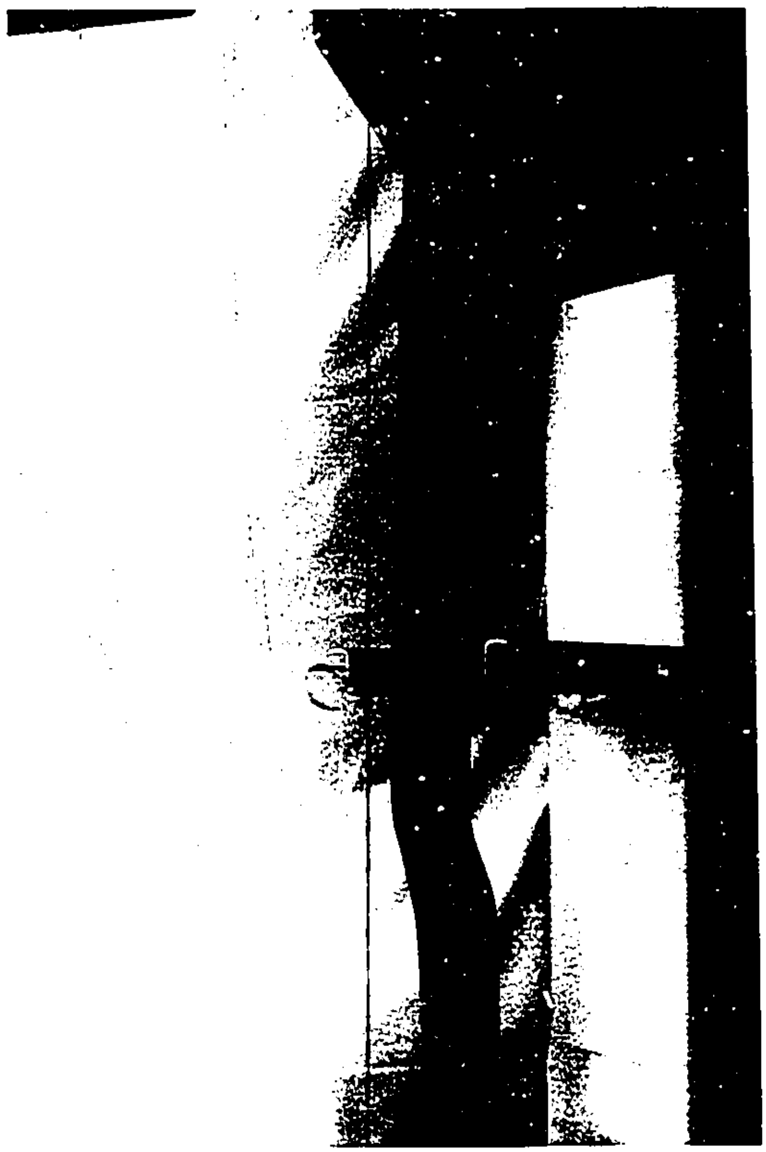


Fig.4.7b

Specimen S4 - 1/4 - 1 showing

Torsional-Flexural Buckling (another view)

Fig.4.7c

Specimen S4 - 1/4 - 1 showing closeup view

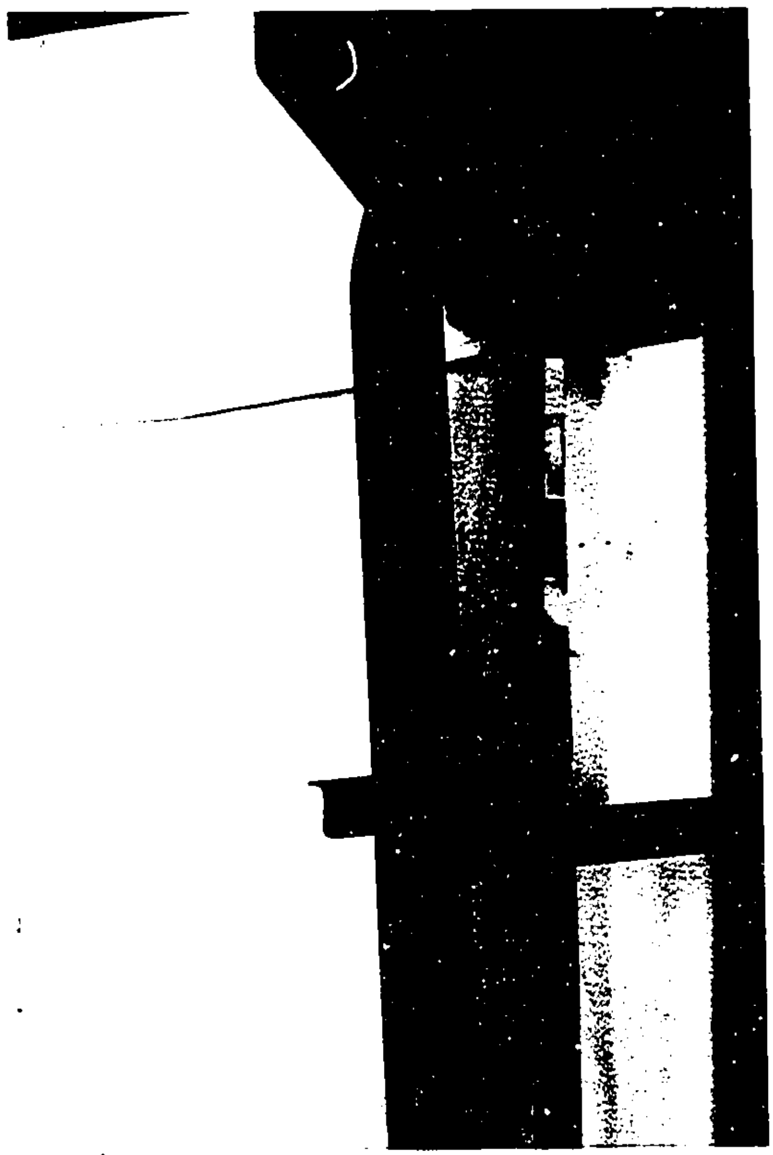


Fig.4.8
Specimen S4 - 1/4 - 3 showing
Torsional-Flexural Buckling

Fig.4.9a
Specimen S5 - 5/16 - 1 showing
Torsional-Flexural Buckling

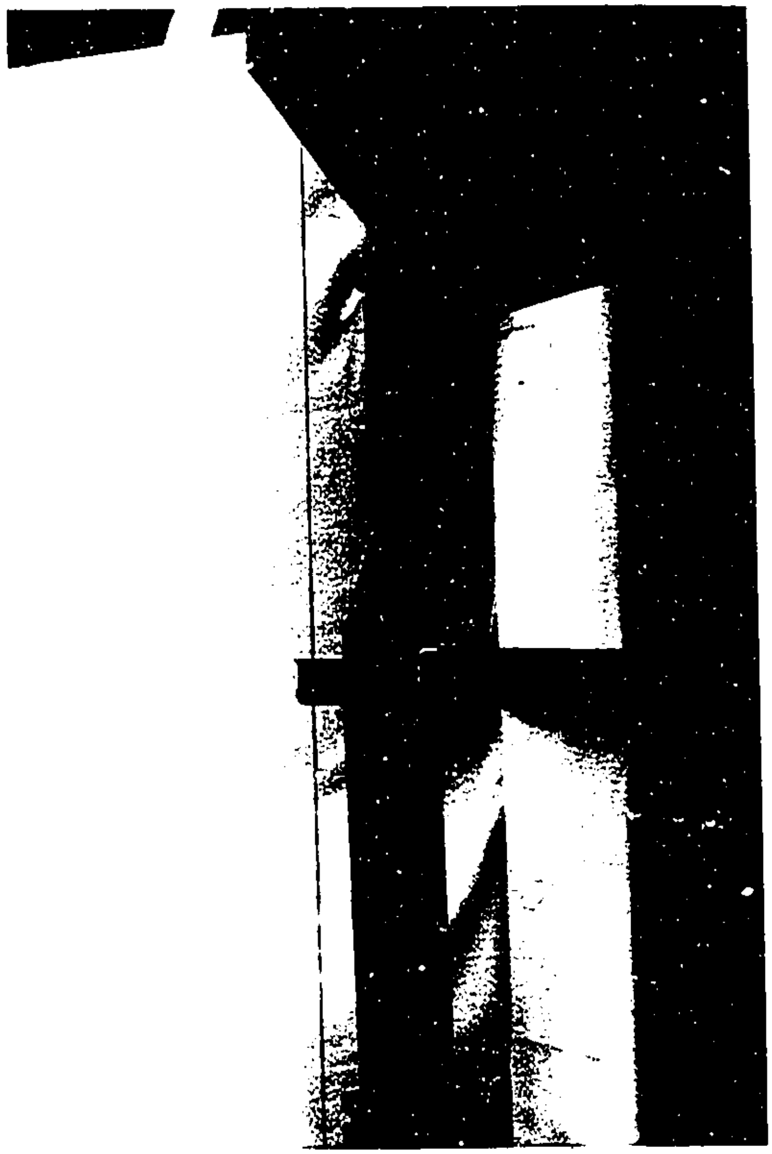


Fig.4.9b
Specimen S5 - 5/16 -1 showing
Torsional-Flexural Buckling (another view)

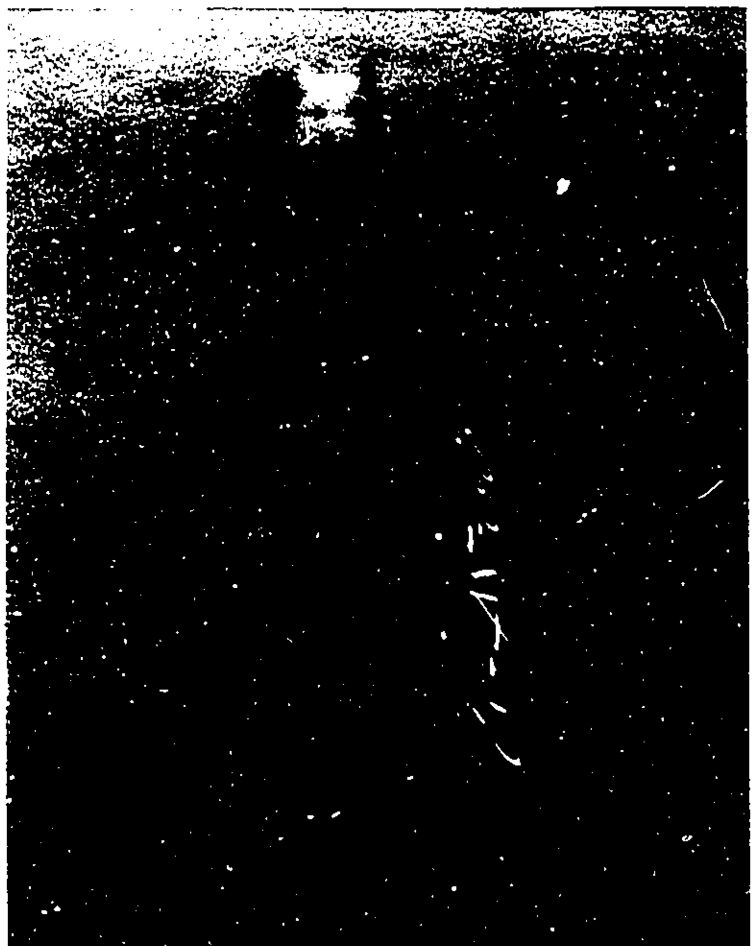


Fig.4.10a
Specimen S3 - 1/4 - 3 showing Major Axis Buckling

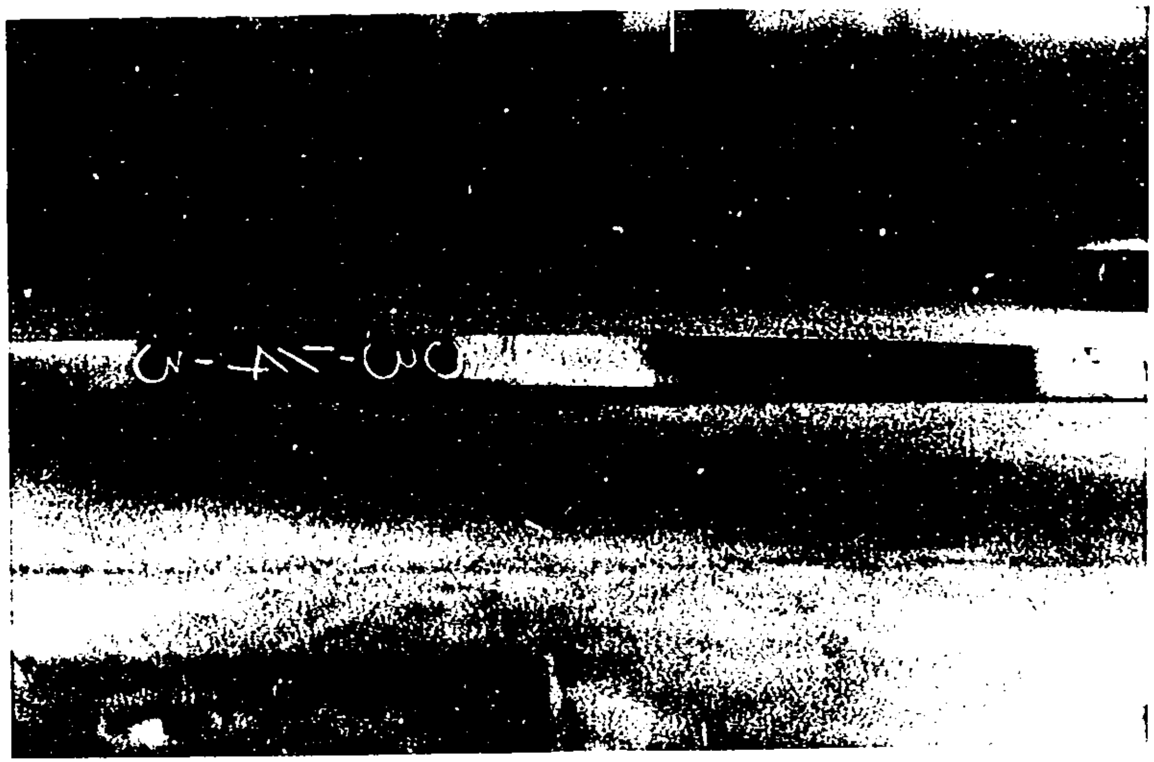


Fig.4.10b

Specimen S3 - 1/4 - 3 showing Minor Axis Buckling

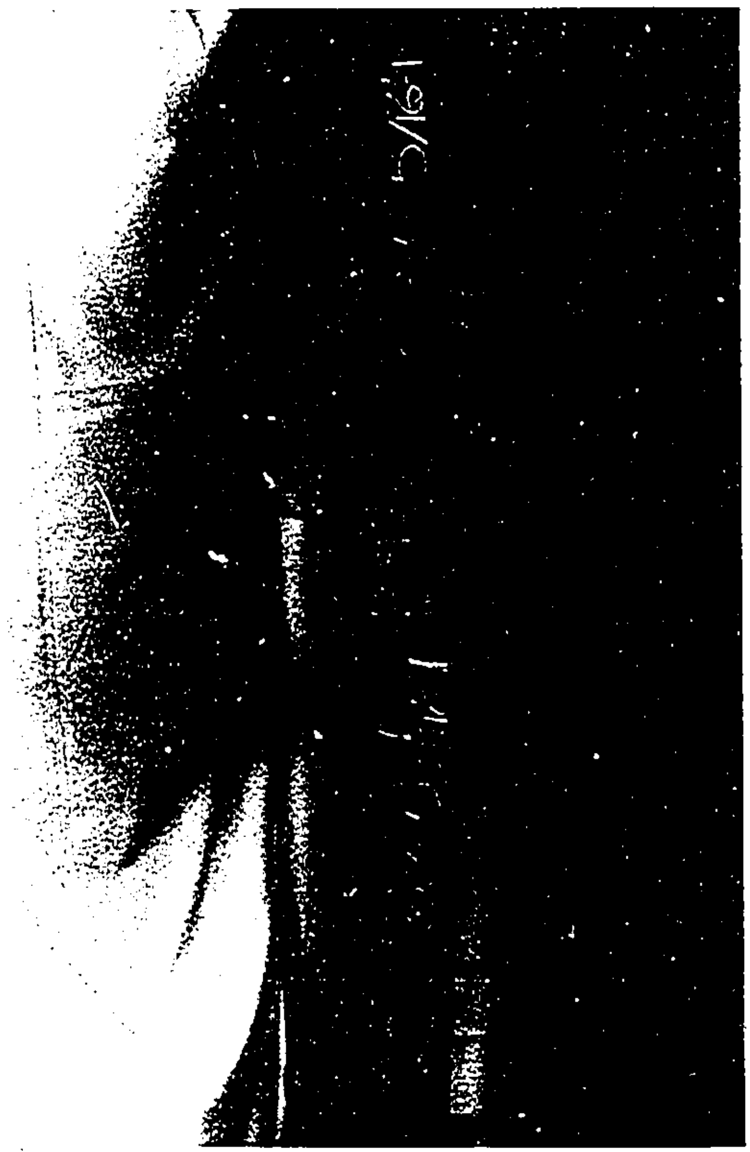


Fig.4.11

Specimen S3.5-5/16-1 showing Minor Axis Buckling

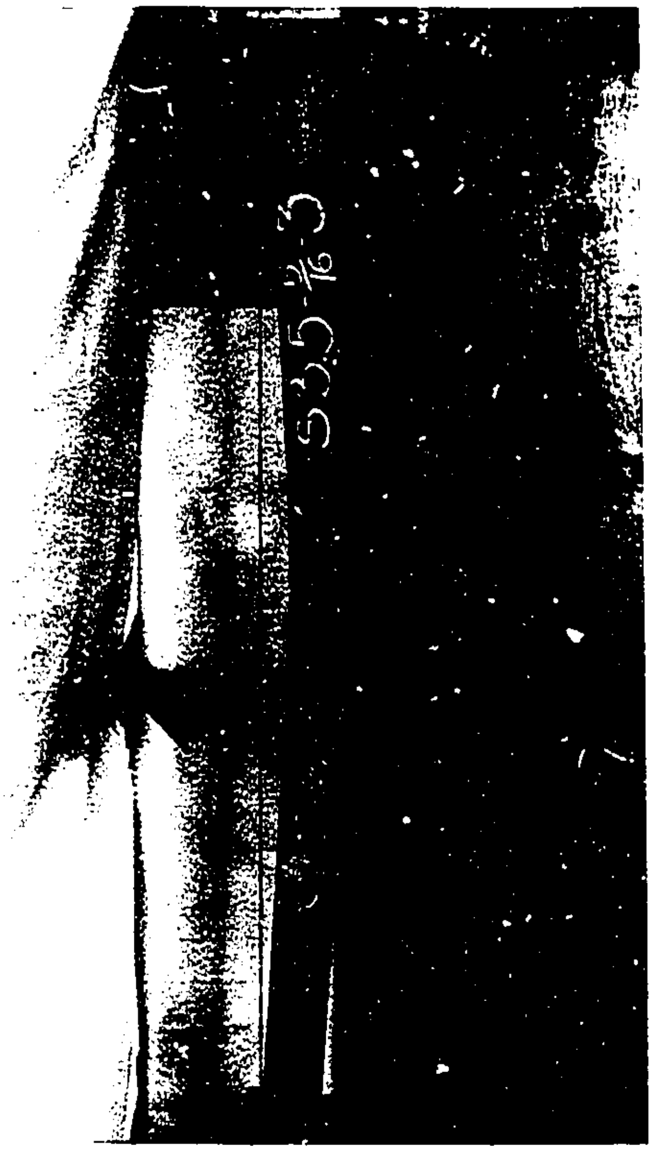


Fig.4.12

Specimen S3.5-5/16-3 showing Minor axis Buckling

Fig.4.13

Specimen S3 - 3/8 - 1 showing Minor Axis Buckling

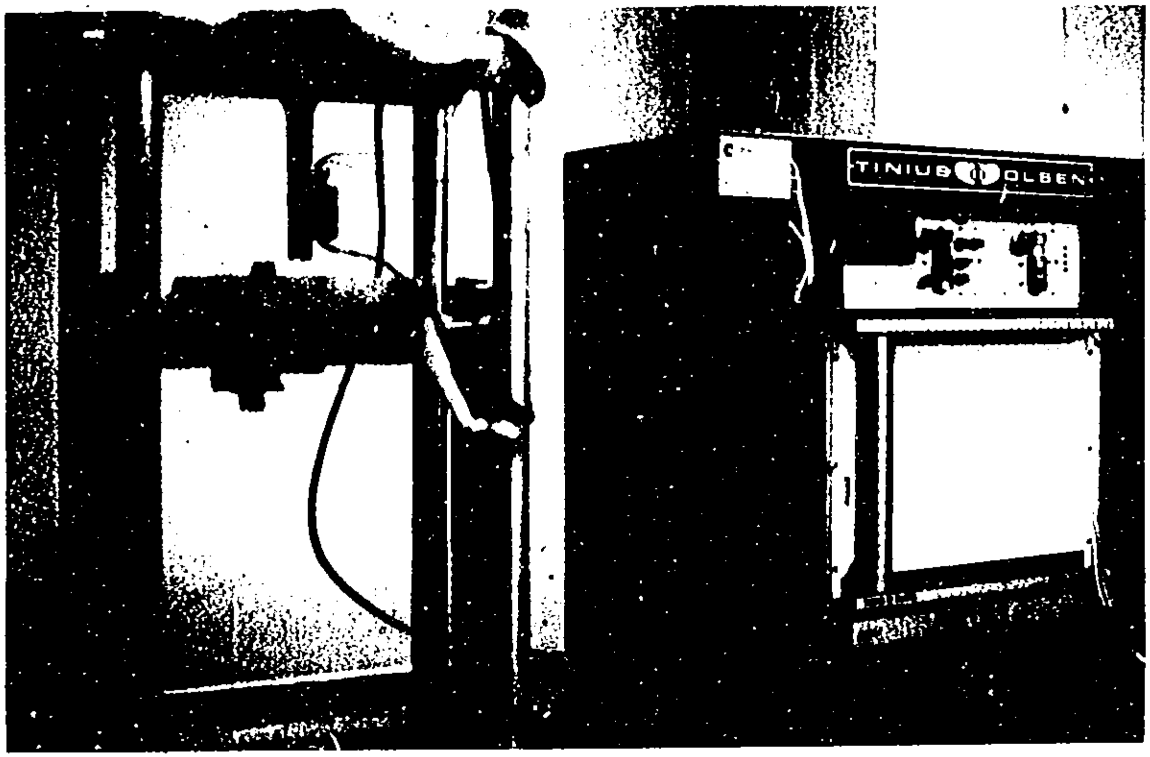


Fig.4.14

Tensile Test Set-up showing Tensile Coupon, Extensometer, X-Y Recorder and Universal Testing Machine

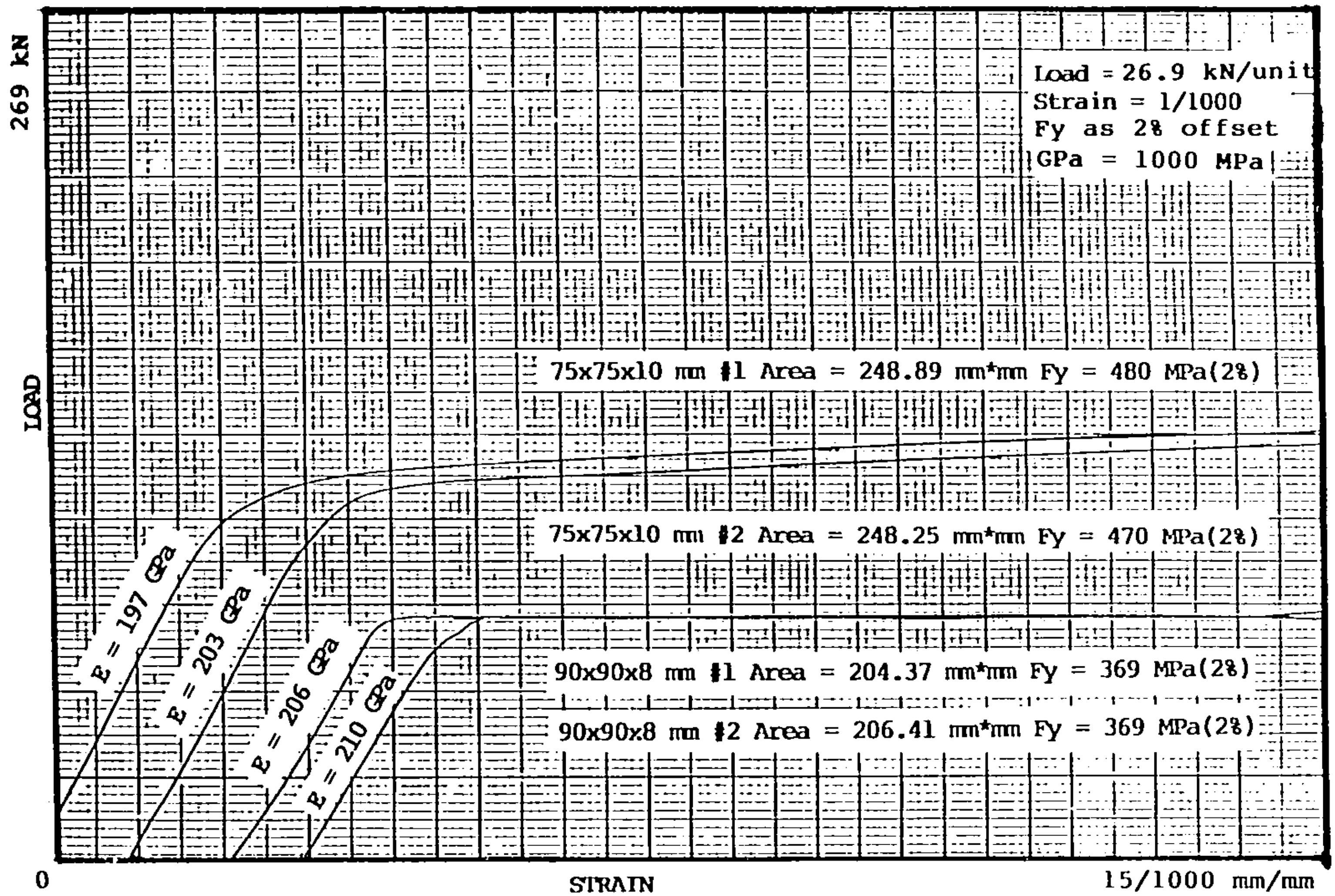


Fig.4.15a

Standard Tension Test Curves - Set A

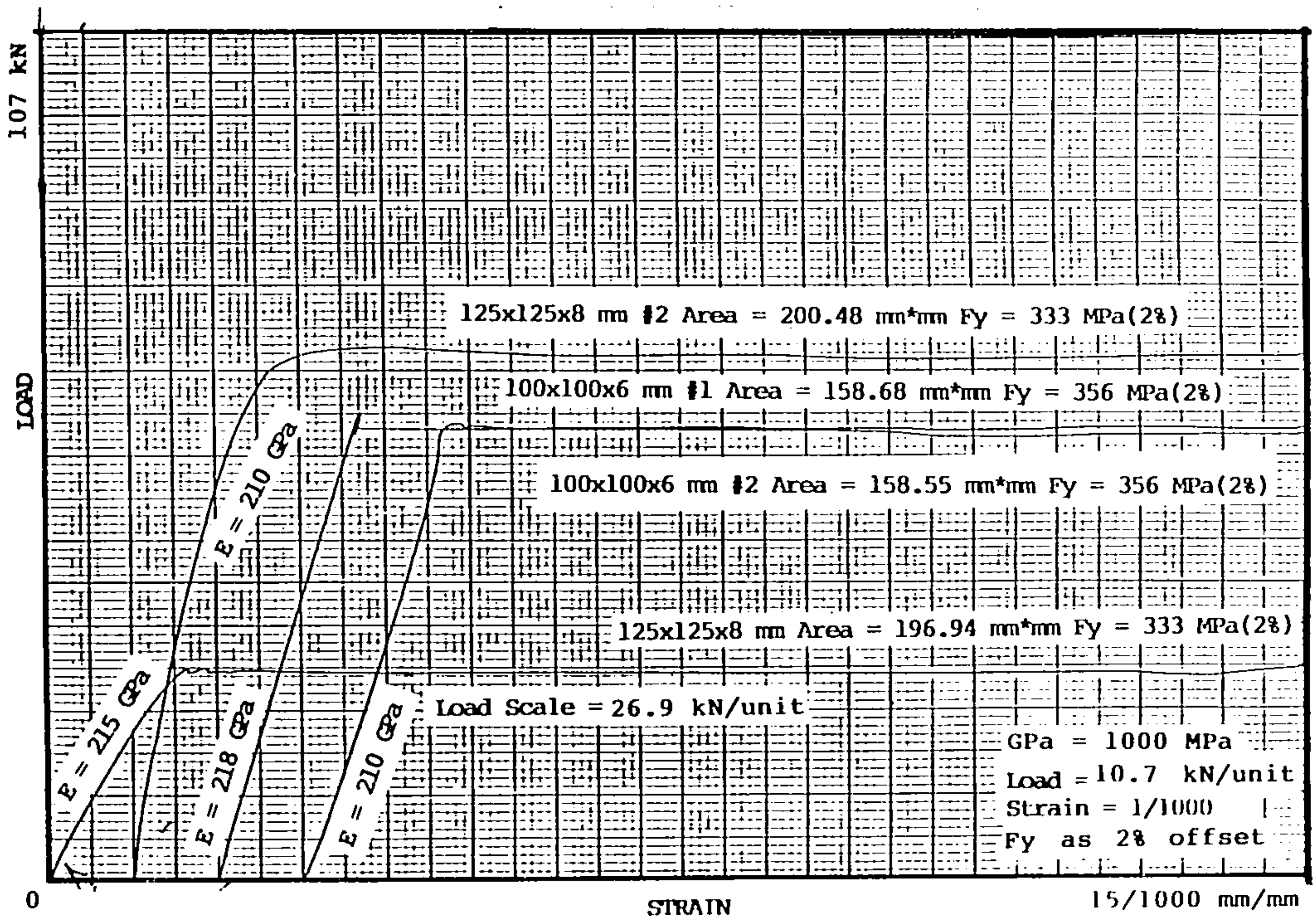


Fig.4.15b

Standard Tension Test Curves - Set B

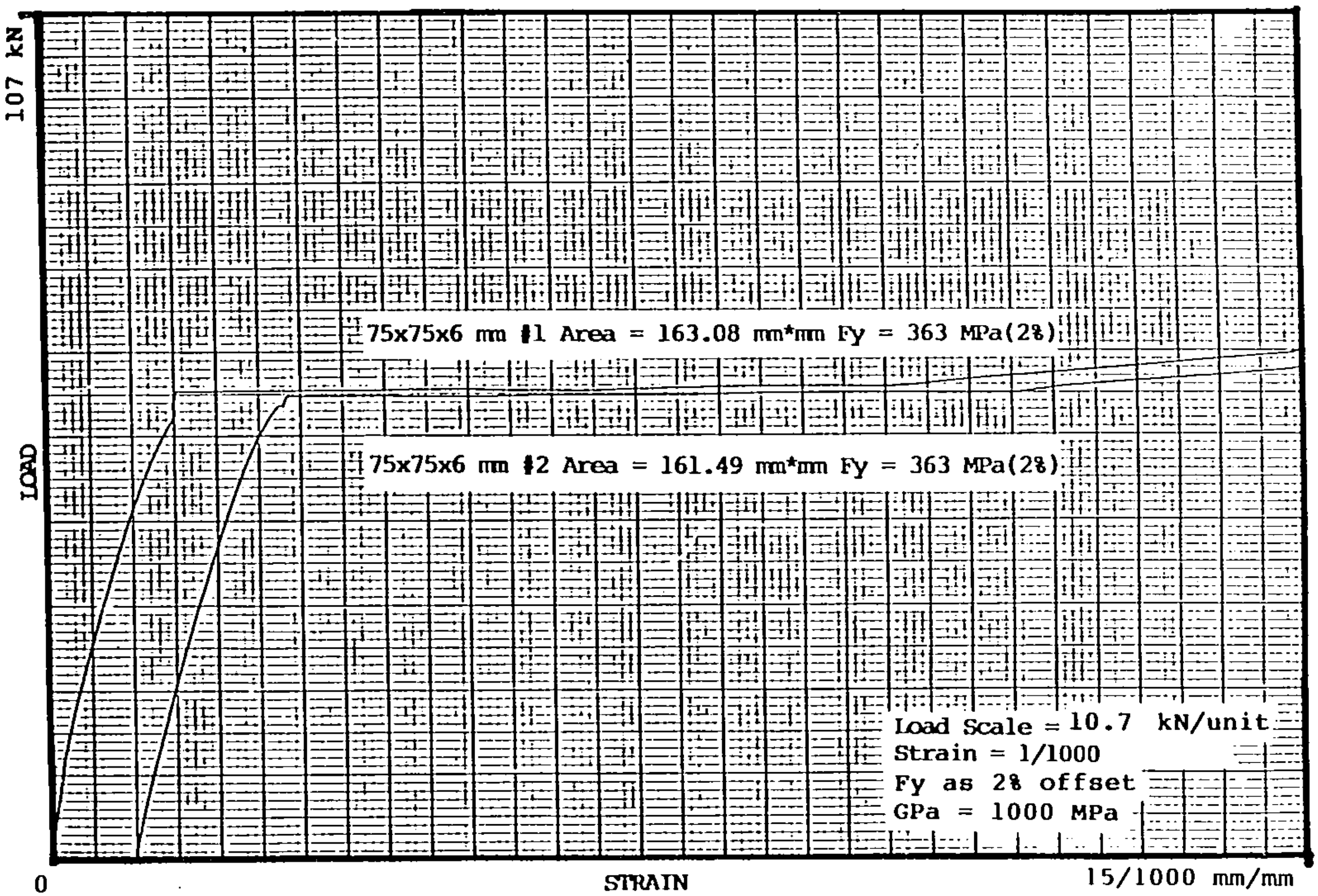


Fig.4.15c

Standard Tension Test Curves - Set C

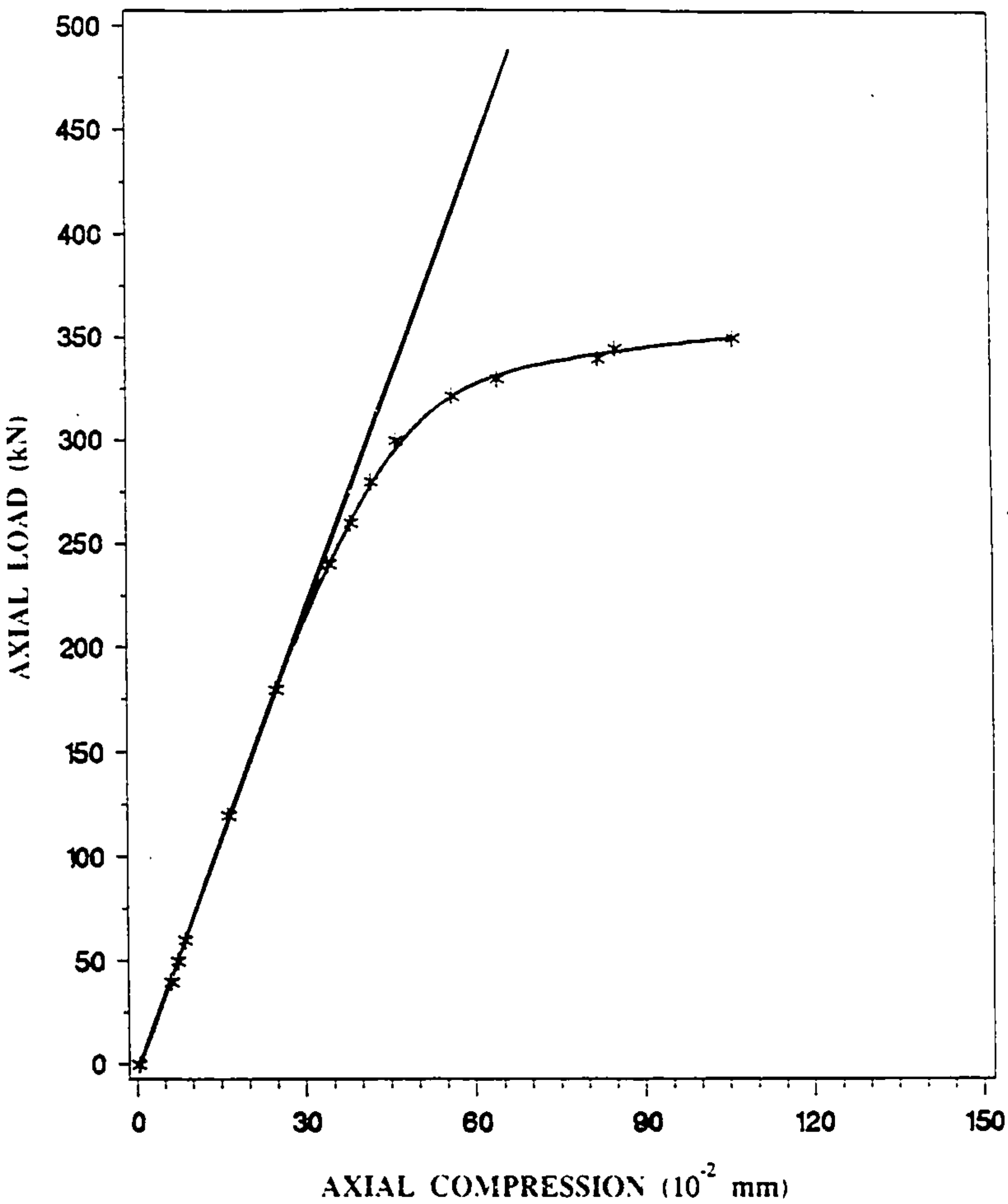


Fig.4.16

STUB-COLUMN TEST RESULTS

for 3x3x1/4 in. SCHIFFLERIZED ANGLE

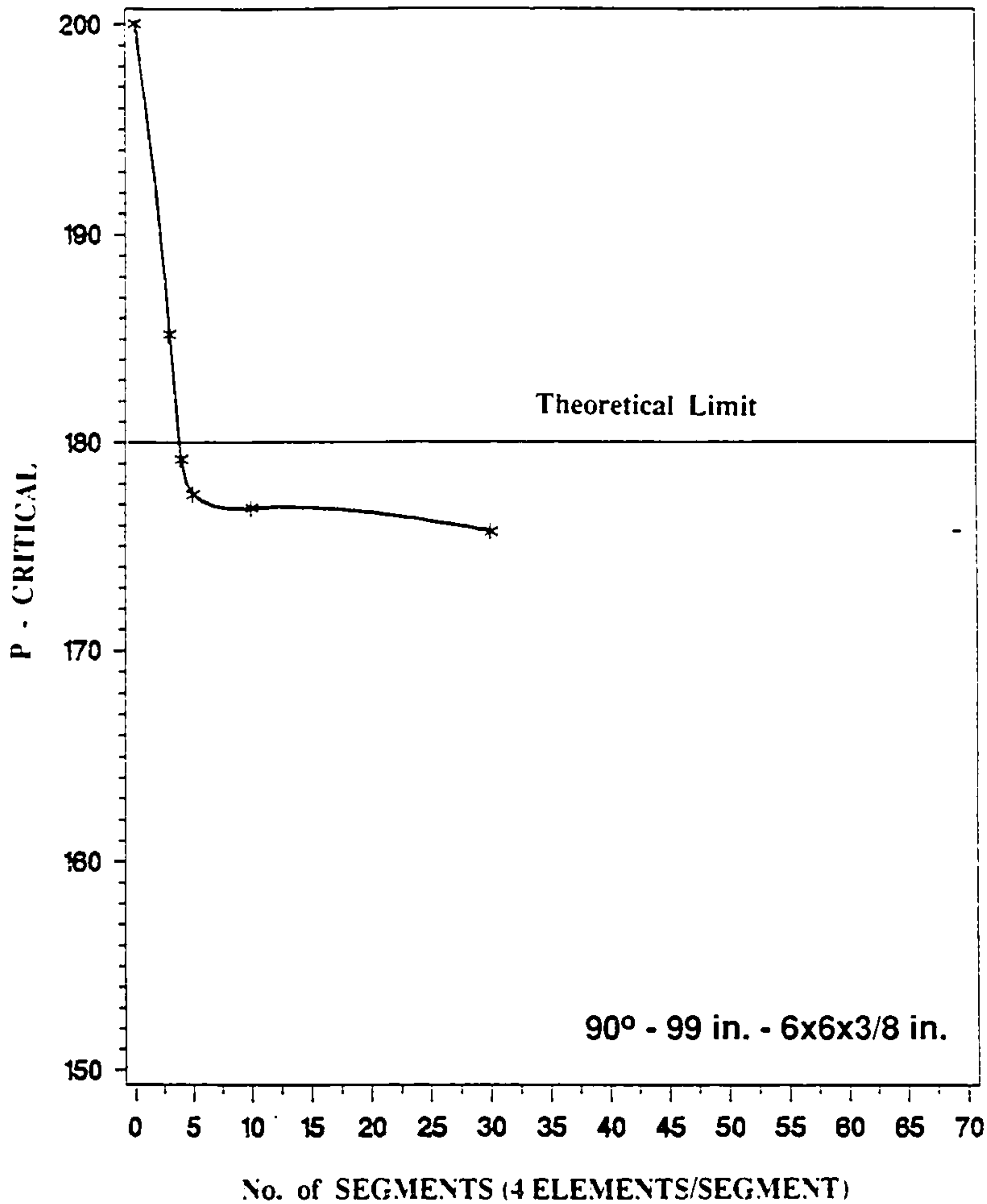


Fig.5.1

TEST FOR CONVERGENCE OF FINITE ELEMENT LOAD FOR FLEXURAL BUCKLING ANALYSIS

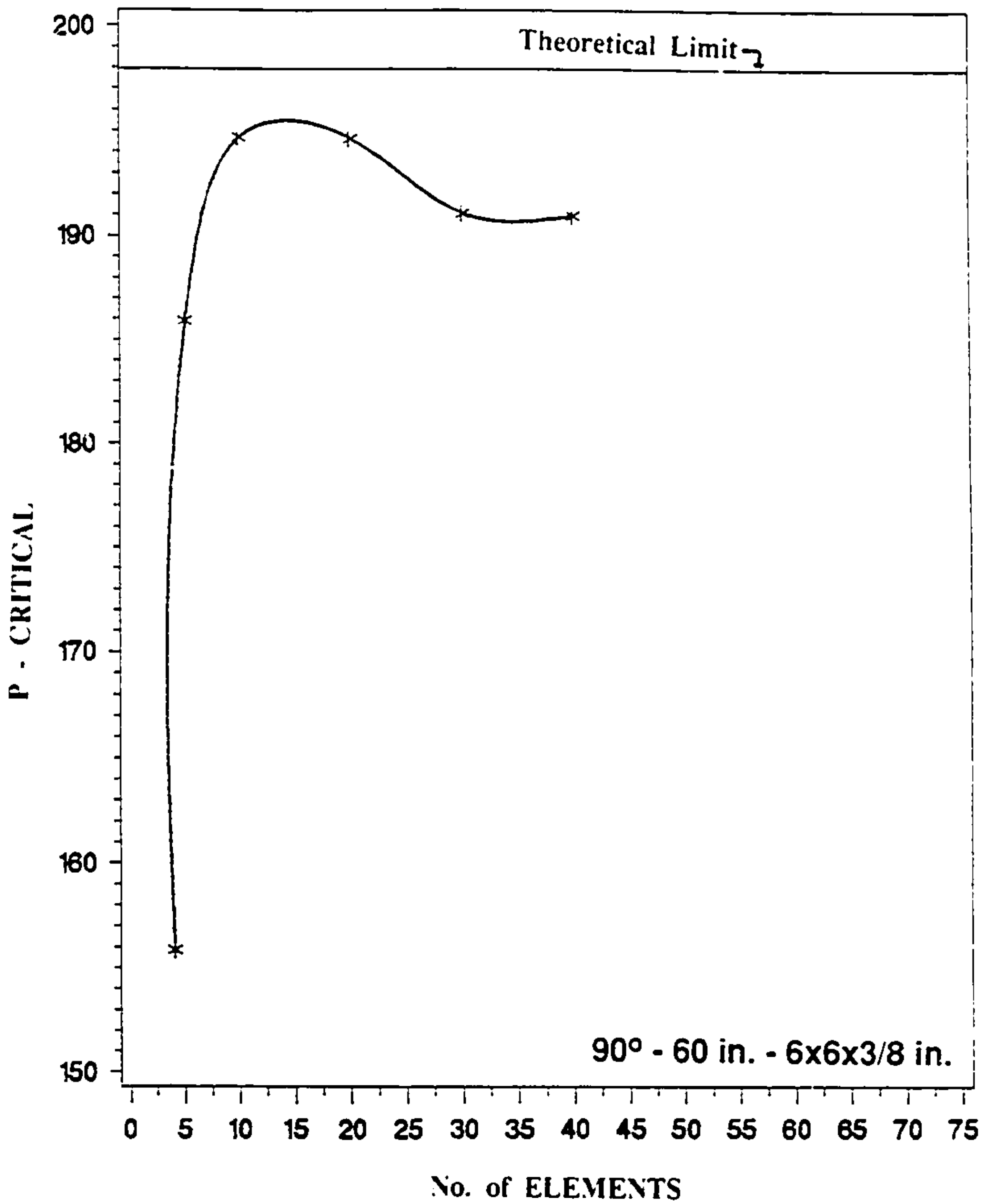


Fig.5.2

TEST FOR CONVERGENCE OF FINITE ELEMENT LOAD FOR TORSIONAL-FLEXURAL BUCKLING ANALYSIS

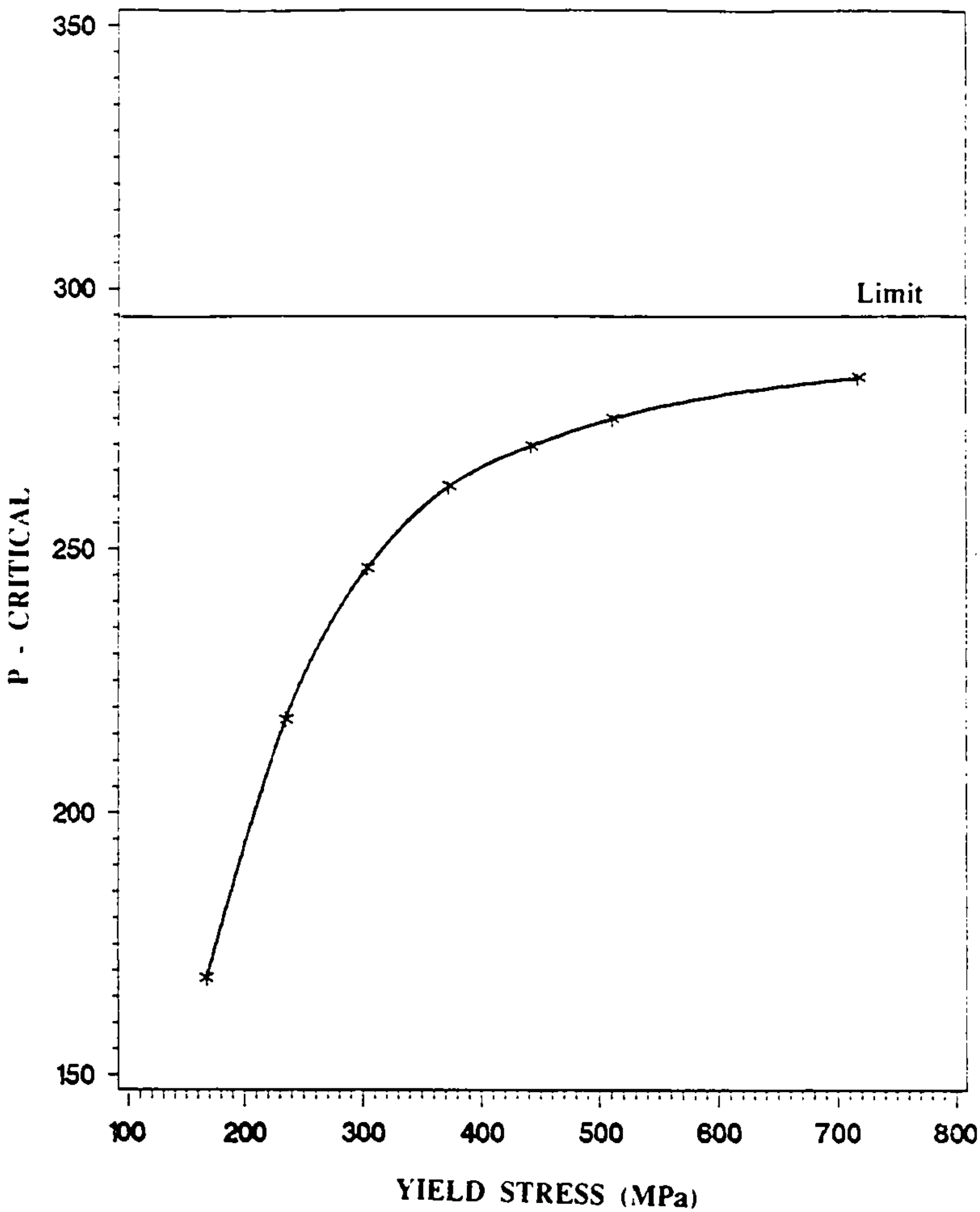


Fig.5.3

LOAD vs YIELD STRESS

75x75x10mm SCHIFFLERIZED ANGLE

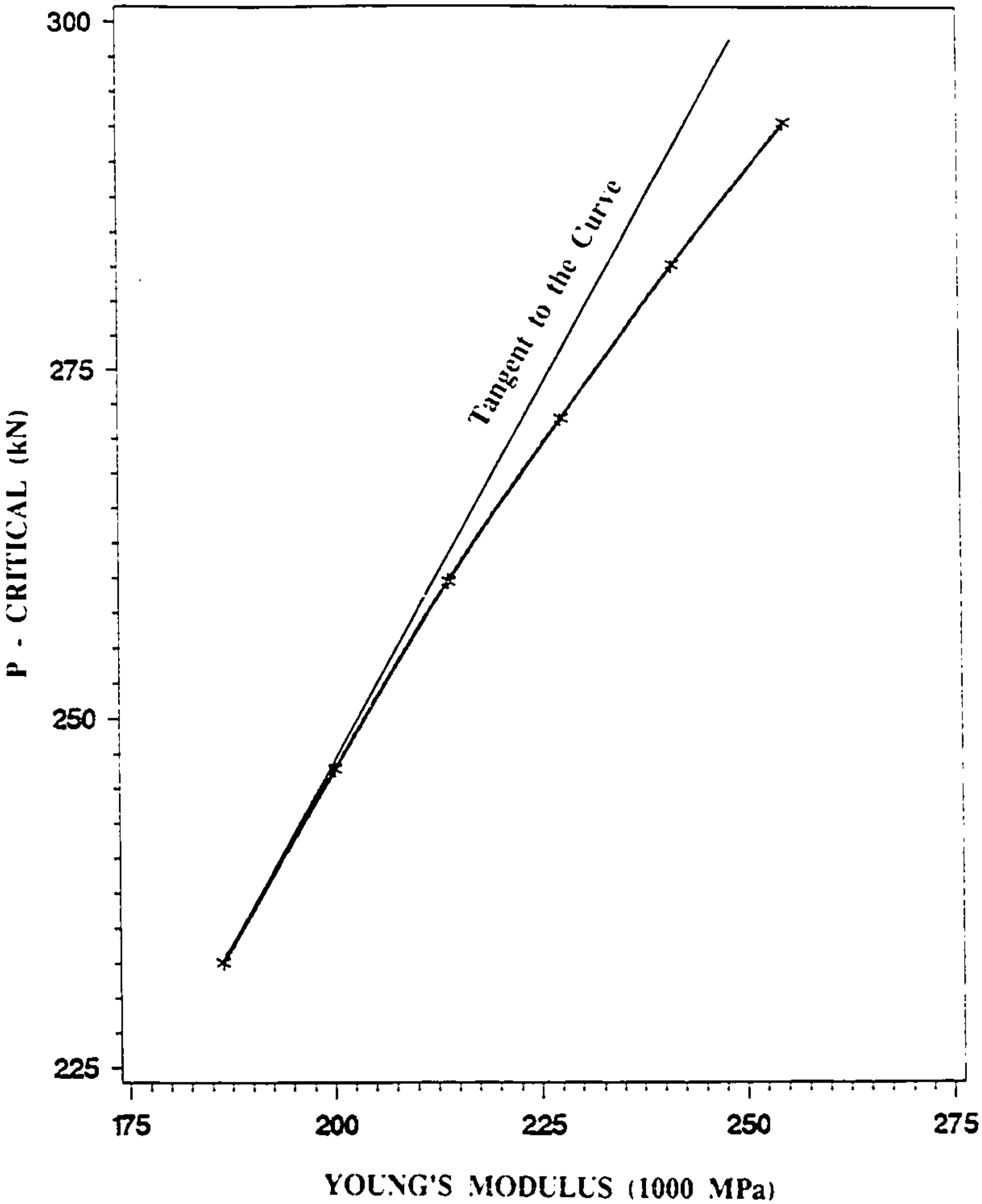


Fig.5.4

LOAD vs YOUNG'S MODULUS

75x75x10mm SCHIFFLERIZED ANGLE

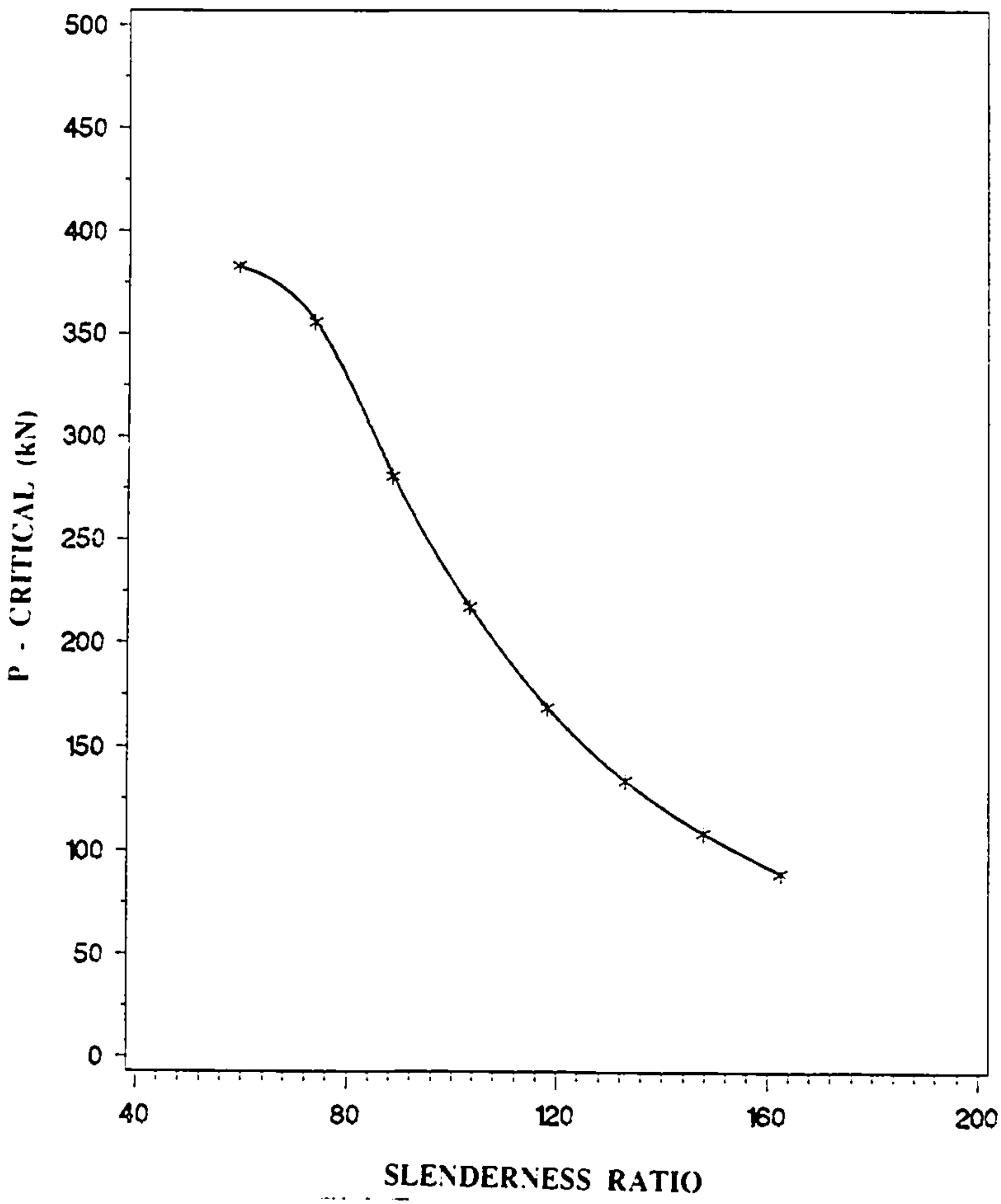


Fig.5.5

LOAD vs SLENDERNESS RATIO

75x75x10mm SCHIFFLERIZED ANGLE

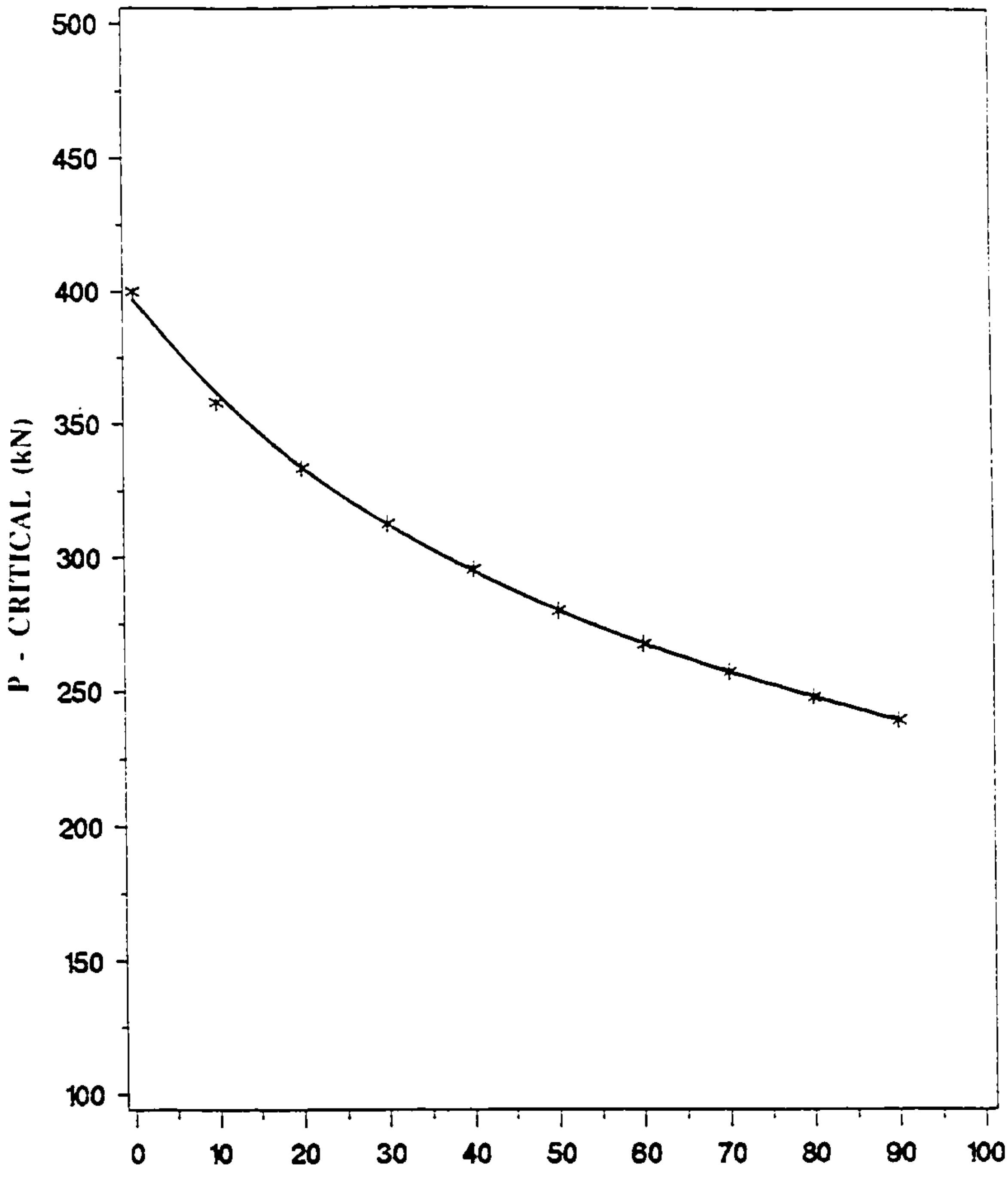


Fig.5.6

LOAD vs RESIDUAL STRESS

75x75x10mm SCHIFFLERIZED ANGLE

Appendix A
TYPICAL FIGURES FOR STRAIN GAUGE READINGS, MID-HEIGHT DEFLECTION AND MID-HEIGHT TWIST

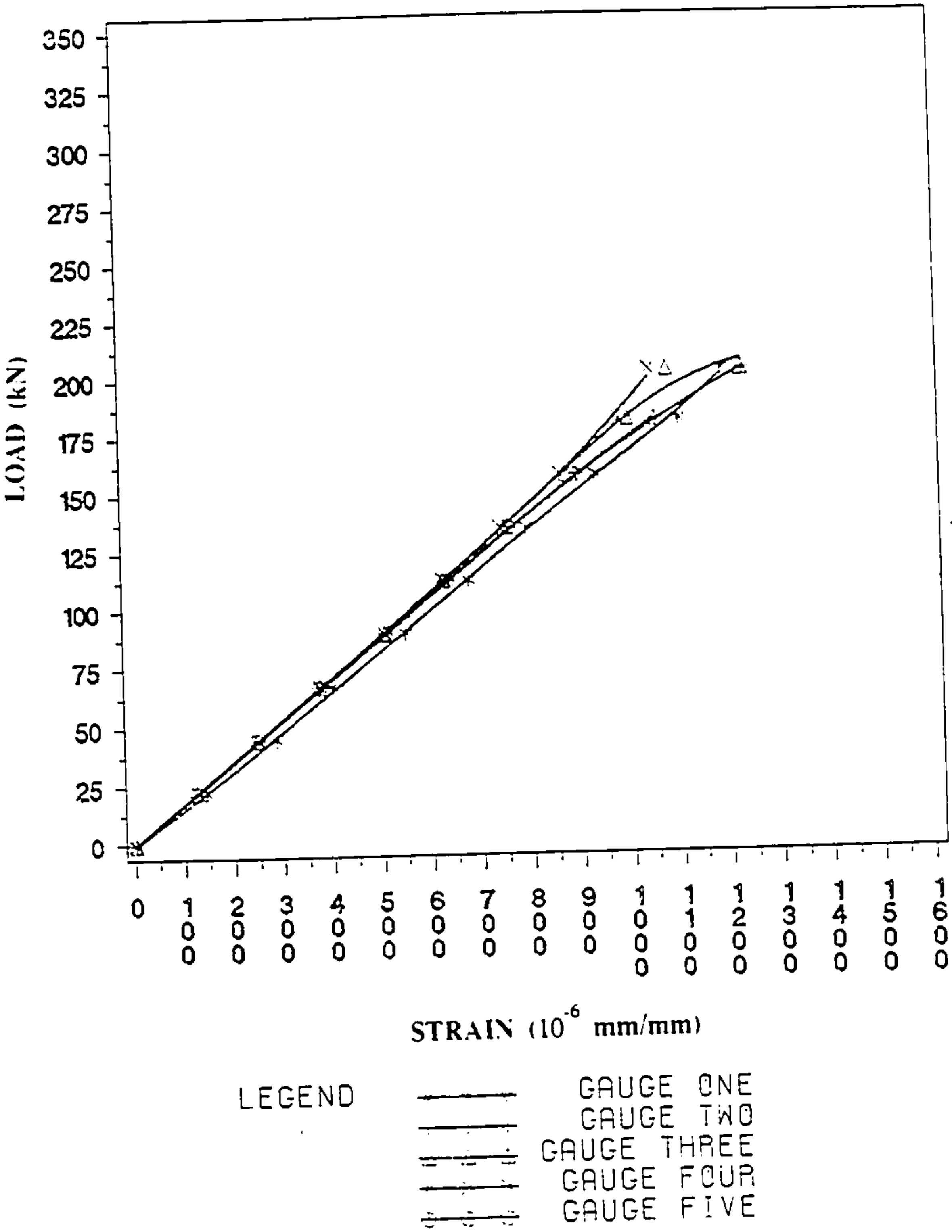


Fig.A.1a

LOAD vs SURFACE STRAIN, SPECIMEN S3 - 1/4 - 3

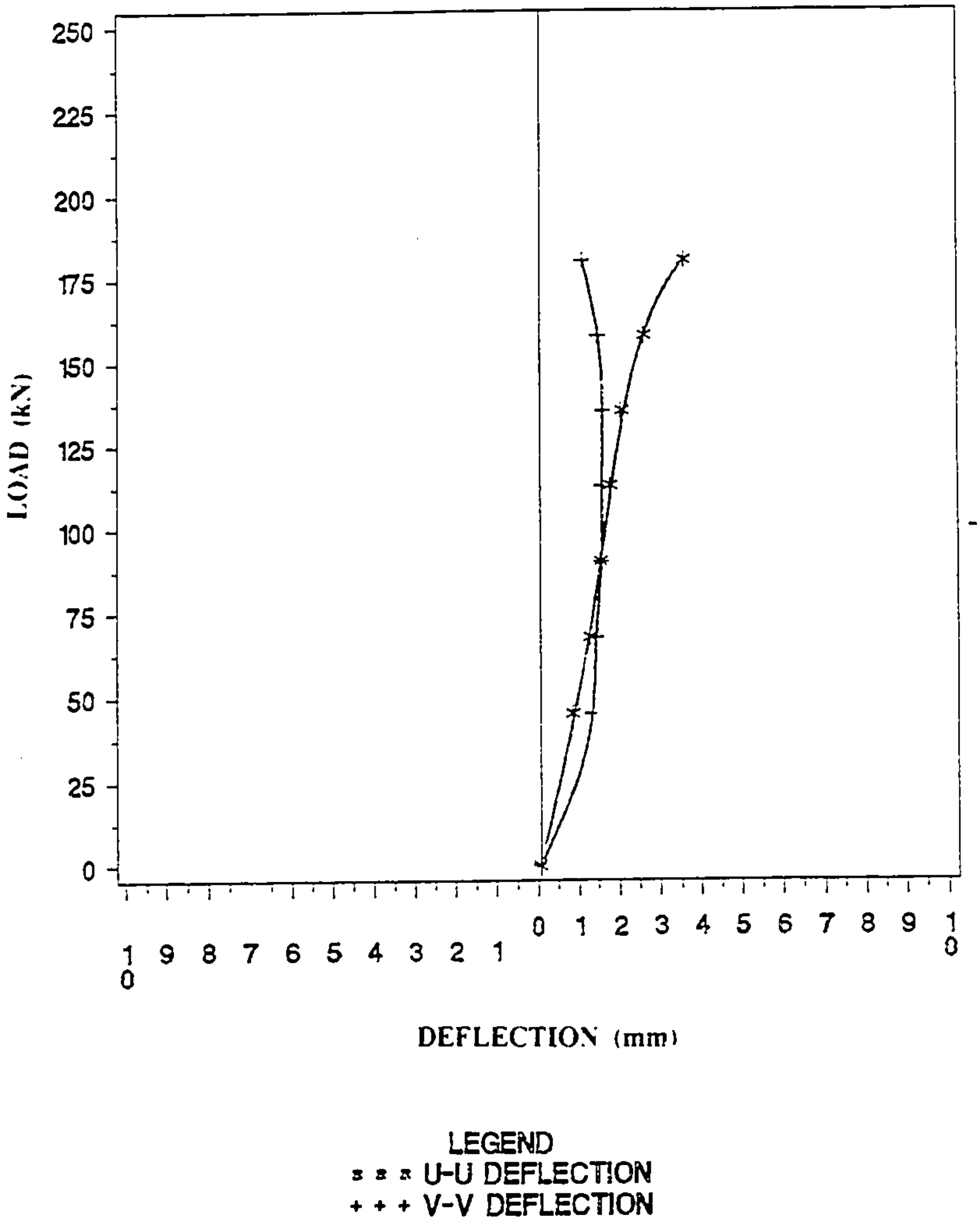


Fig.A.1b

LOAD vs DEFLECTION, SPECIMEN S3 - 1/4 - 3

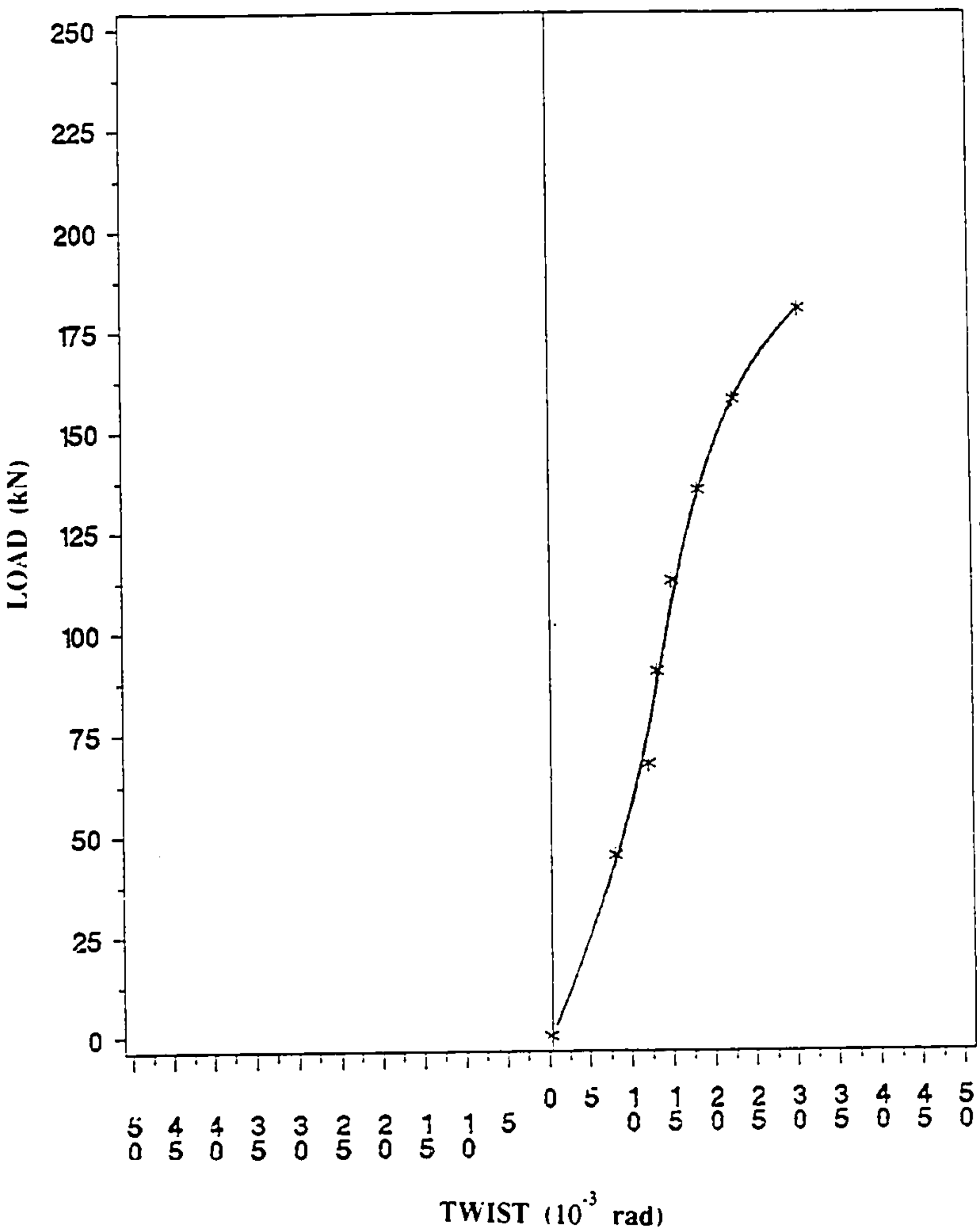


Fig.A.1c

LOAD vs MID-HEIGHT TWIST, SPECIMEN S3 - 1/4 - 3

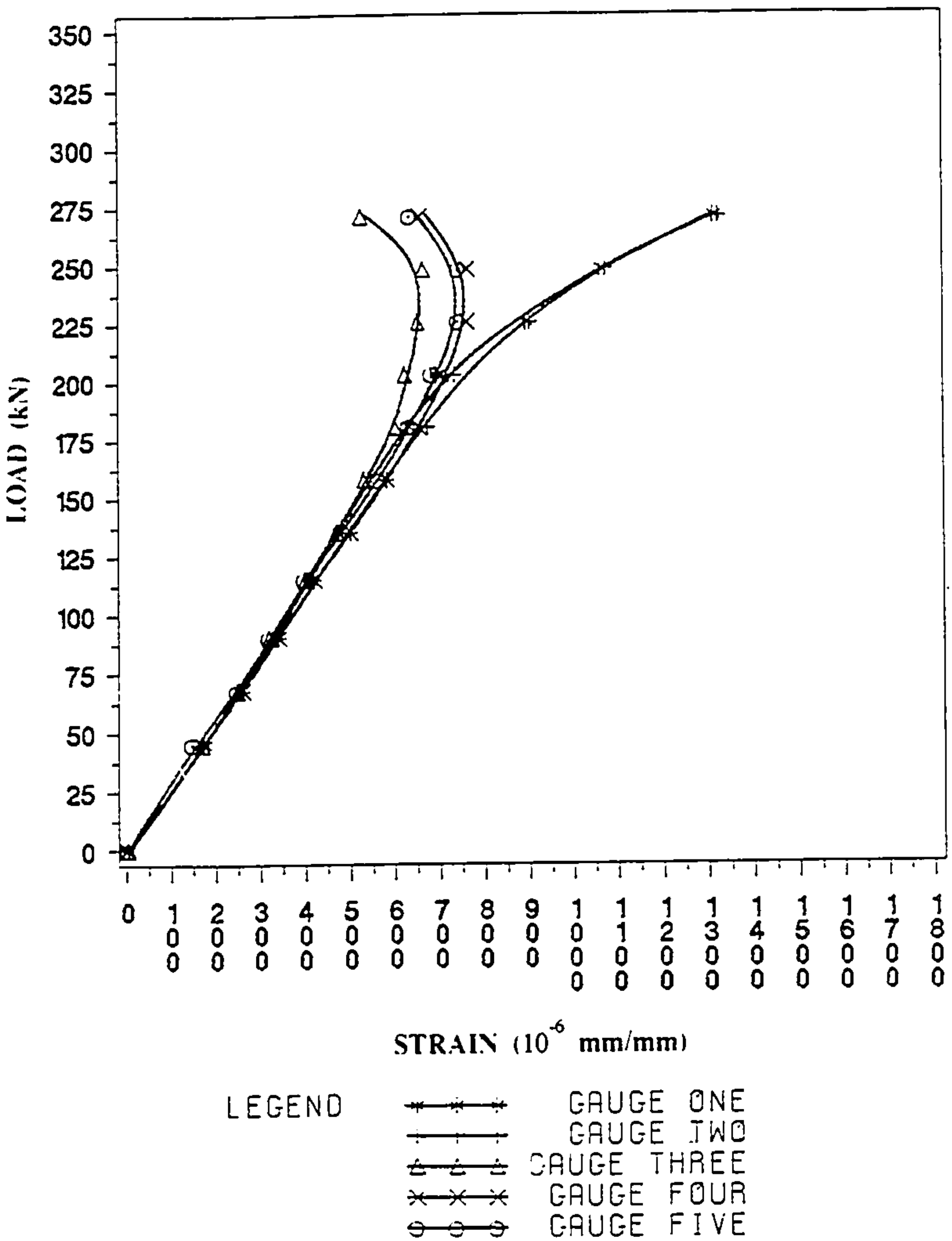
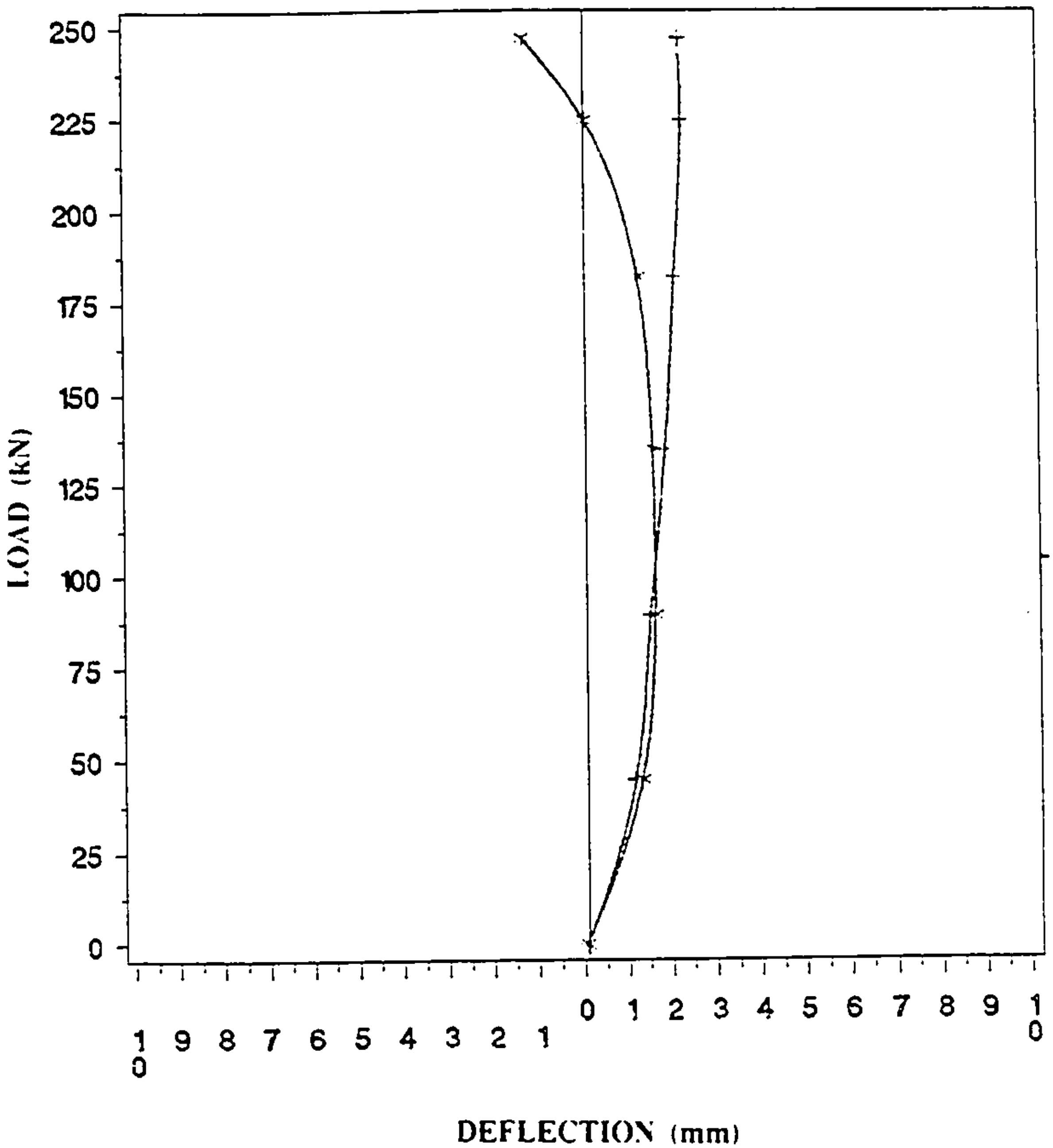


Fig.A.2a

LOAD vs SURFACE STRAIN, SPECIMEN S3 - 3/8 - 2



LEGEND
x x x U-U DEFLECTION
+ + + V-V DEFLECTION

Fig.A.2b

LOAD vs DEFLECTION, SPECIMEN S3 - 3/8 - 2

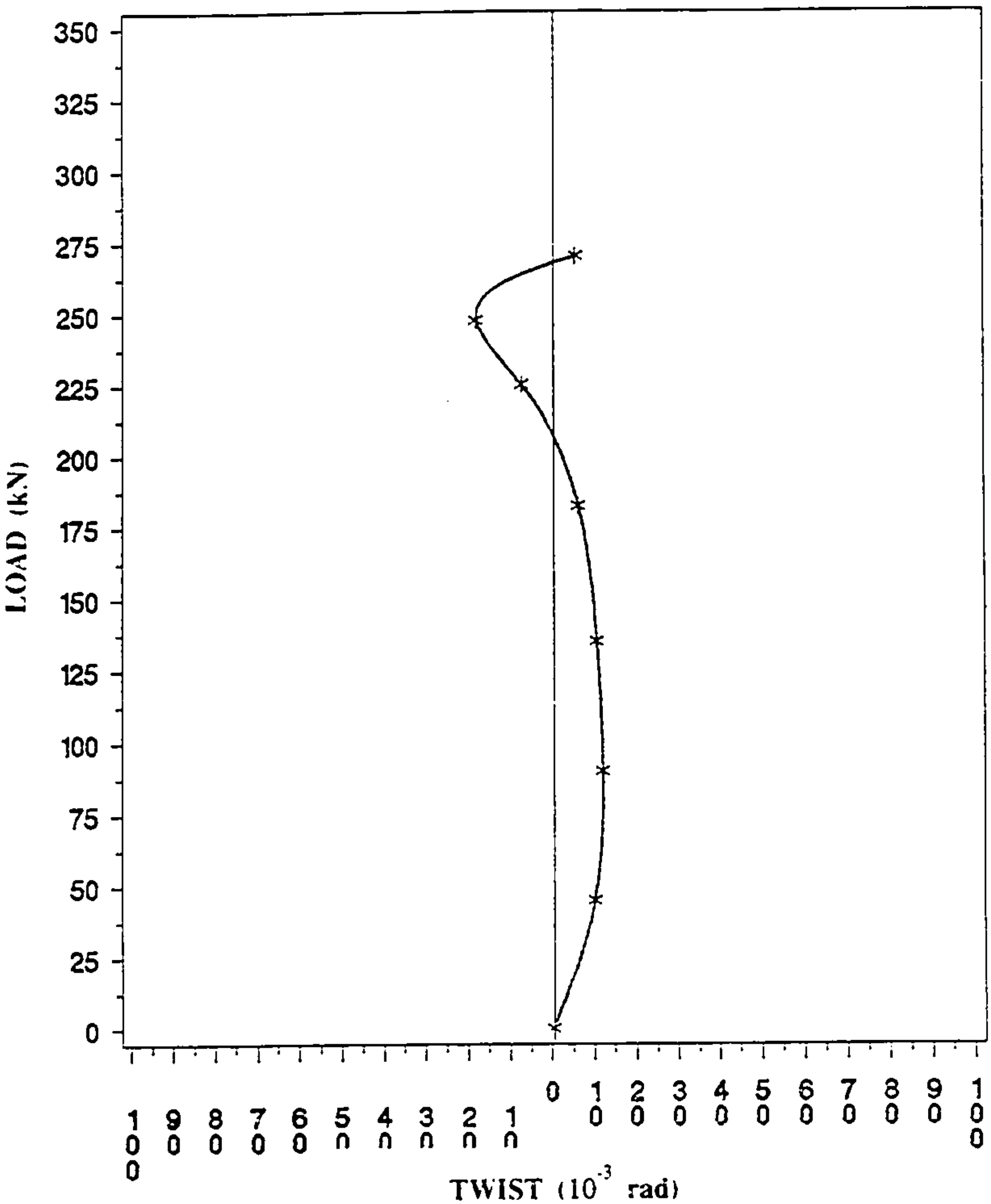


Fig.A.2c

LOAD vs MID-HEIGHT TWIST, SPECIMEN S3 - 3/8 - 2

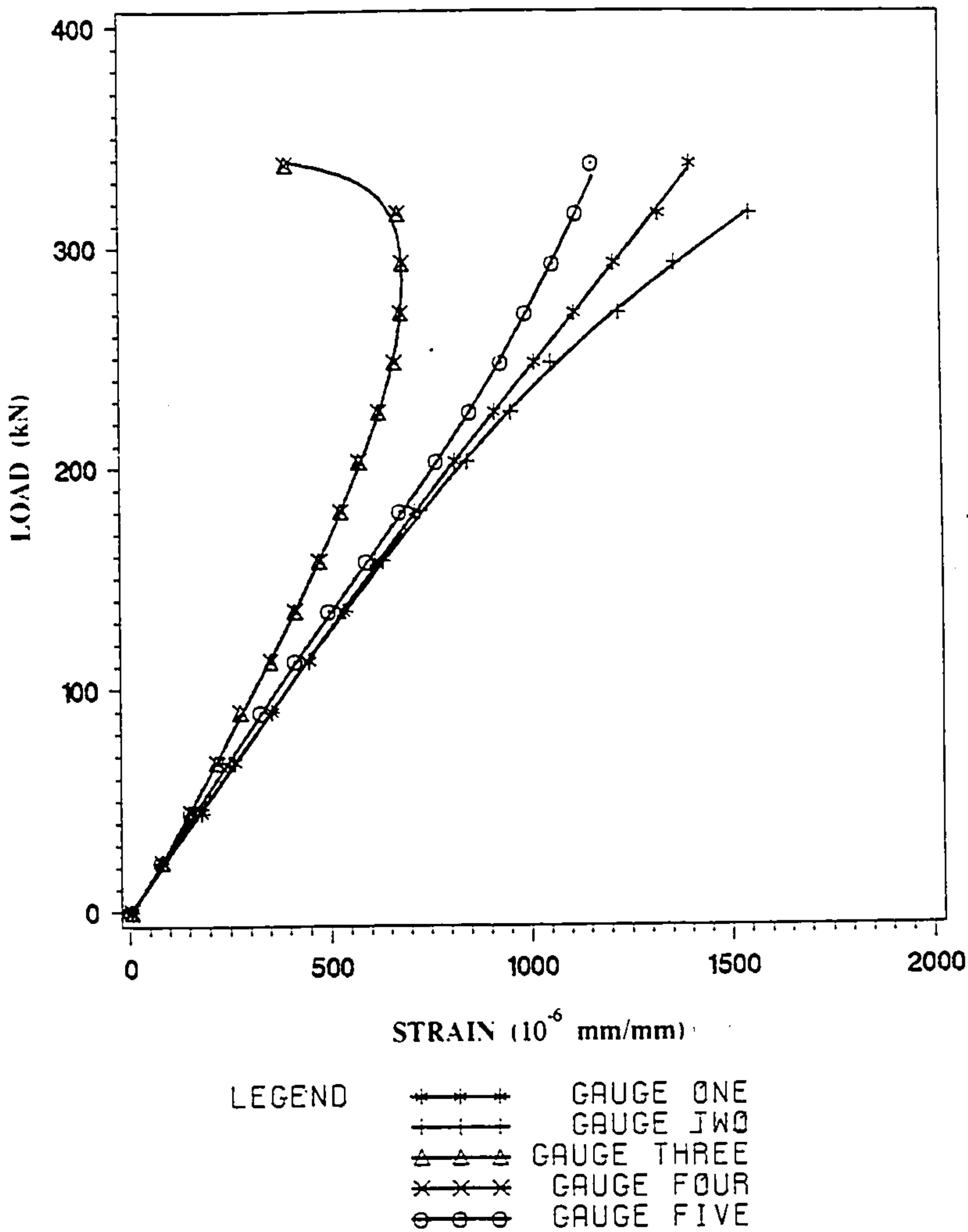
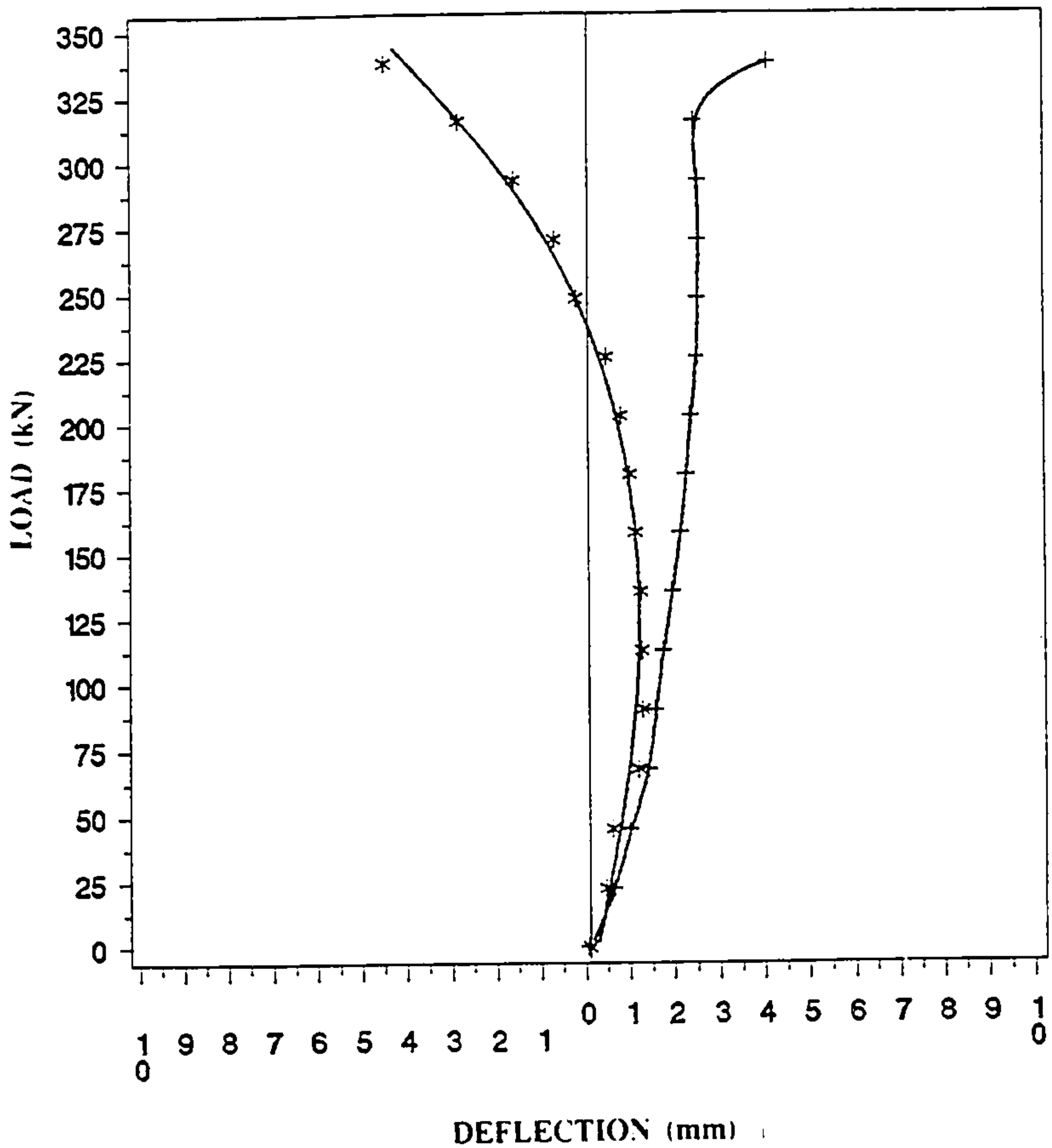


Fig.A.3a

LOAD vs SURFACE STRAIN, SPECIMEN S3.5 - 5/16 - 1



LEGEND
* * * U-U DISPLACEMENT
+ + + V-V DISPLACEMENT

Fig.A.3b

LOAD vs DEFLECTION, SPECIMEN S3.5-5/16-1

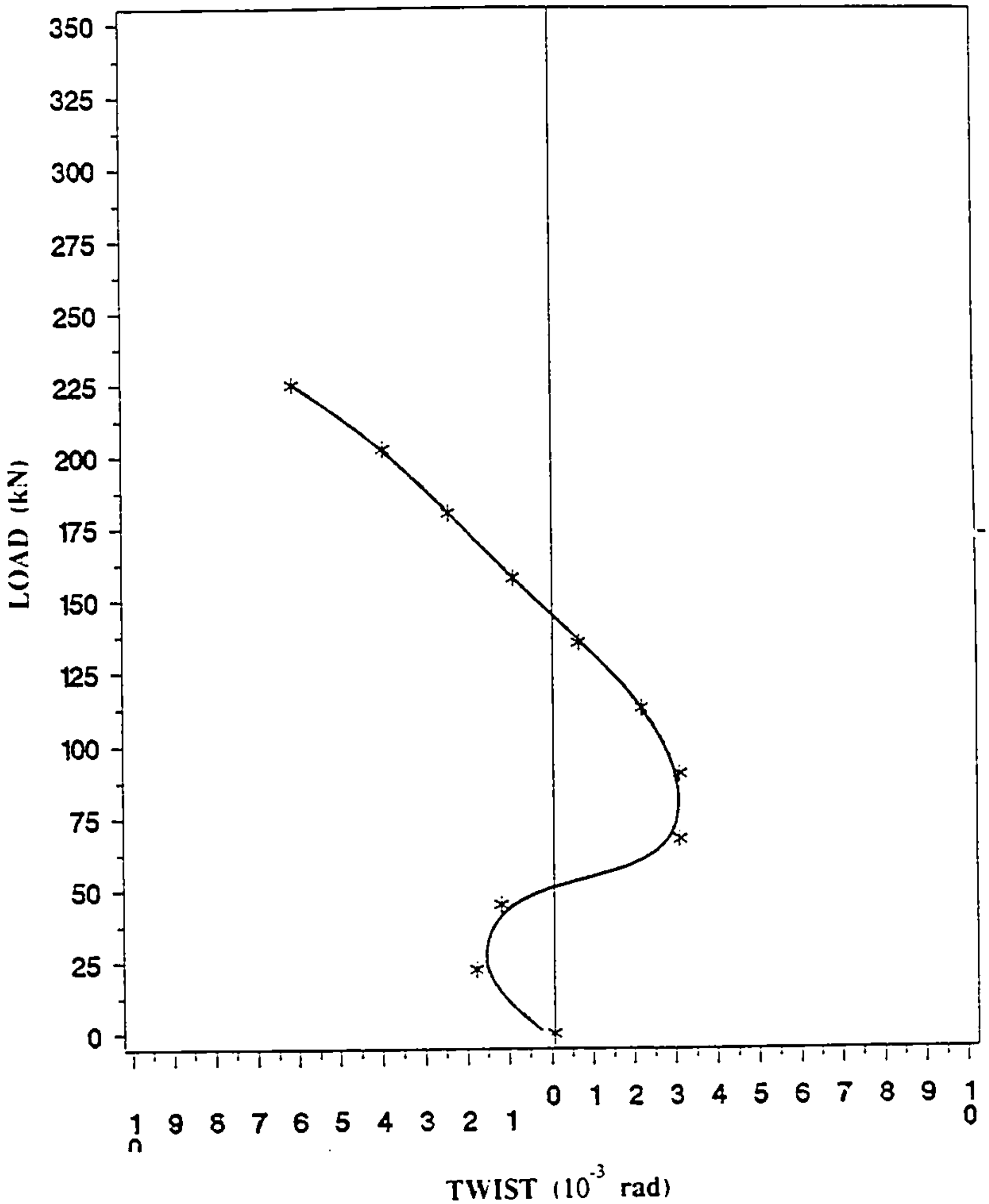


Fig.A.3c

LOAD vs MID-HEIGHT TWIST, SPECIMEN S3.5-5/16-1

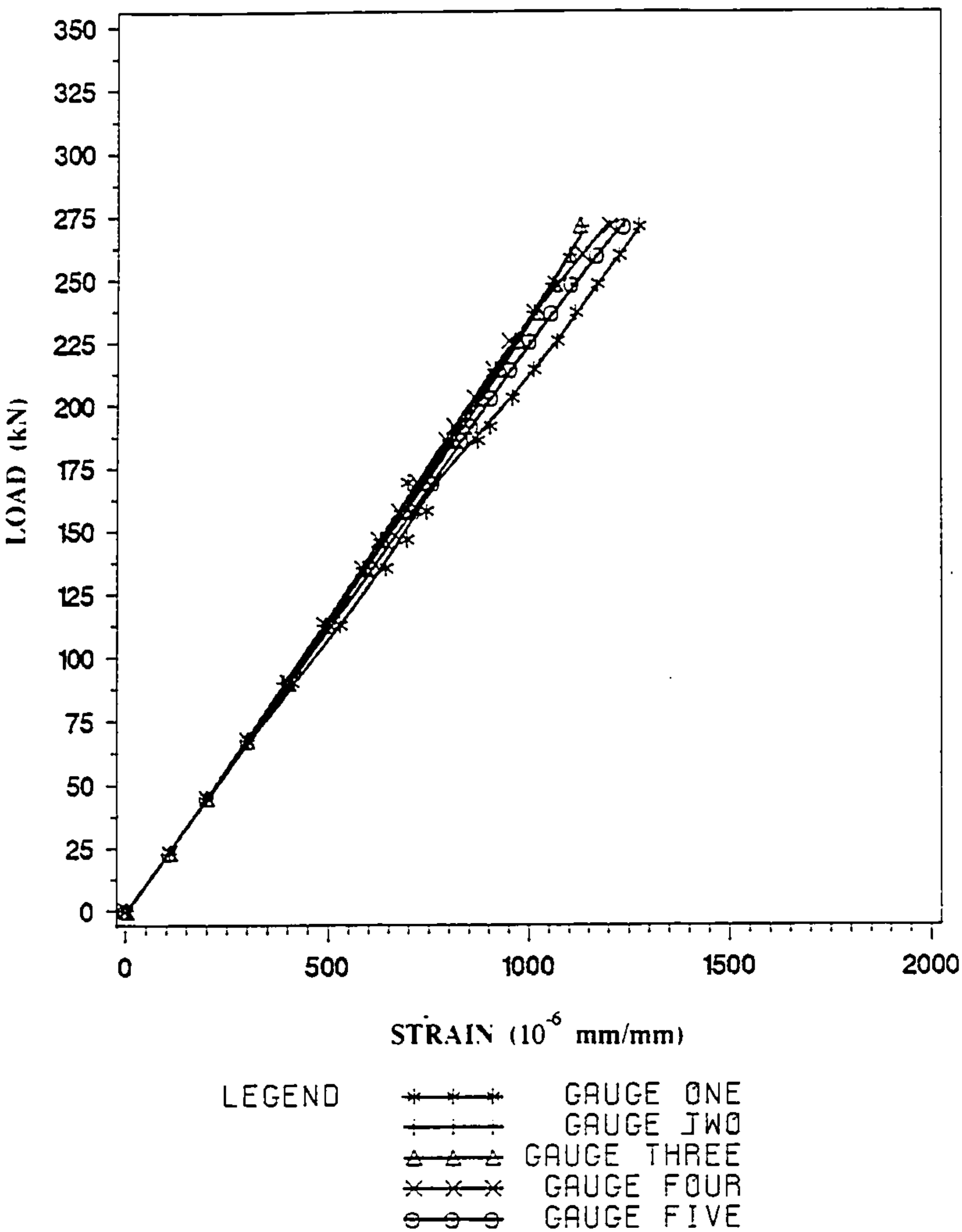
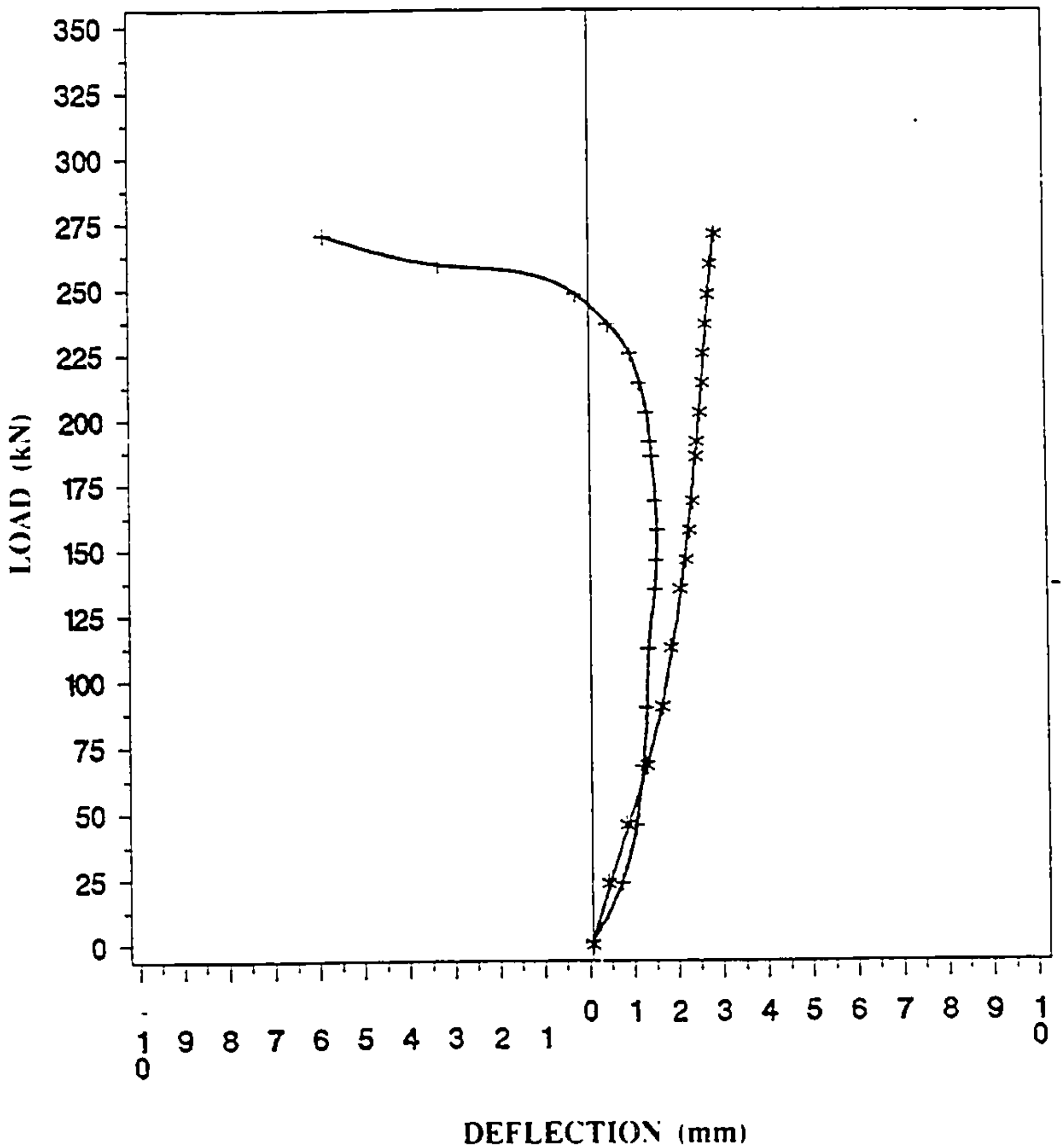


Fig.A.4a

LOAD vs SURFACE STRAIN, SPECIMEN S4 - 1/4 - 1



LEGEND
¤ ¤ ¤ U-U DEFLECTION
+ + + V-V DEFLECTION

Fig.A.4b

LOAD vs DEFLECTION, SPECIMEN S4 - 1/4 - 1

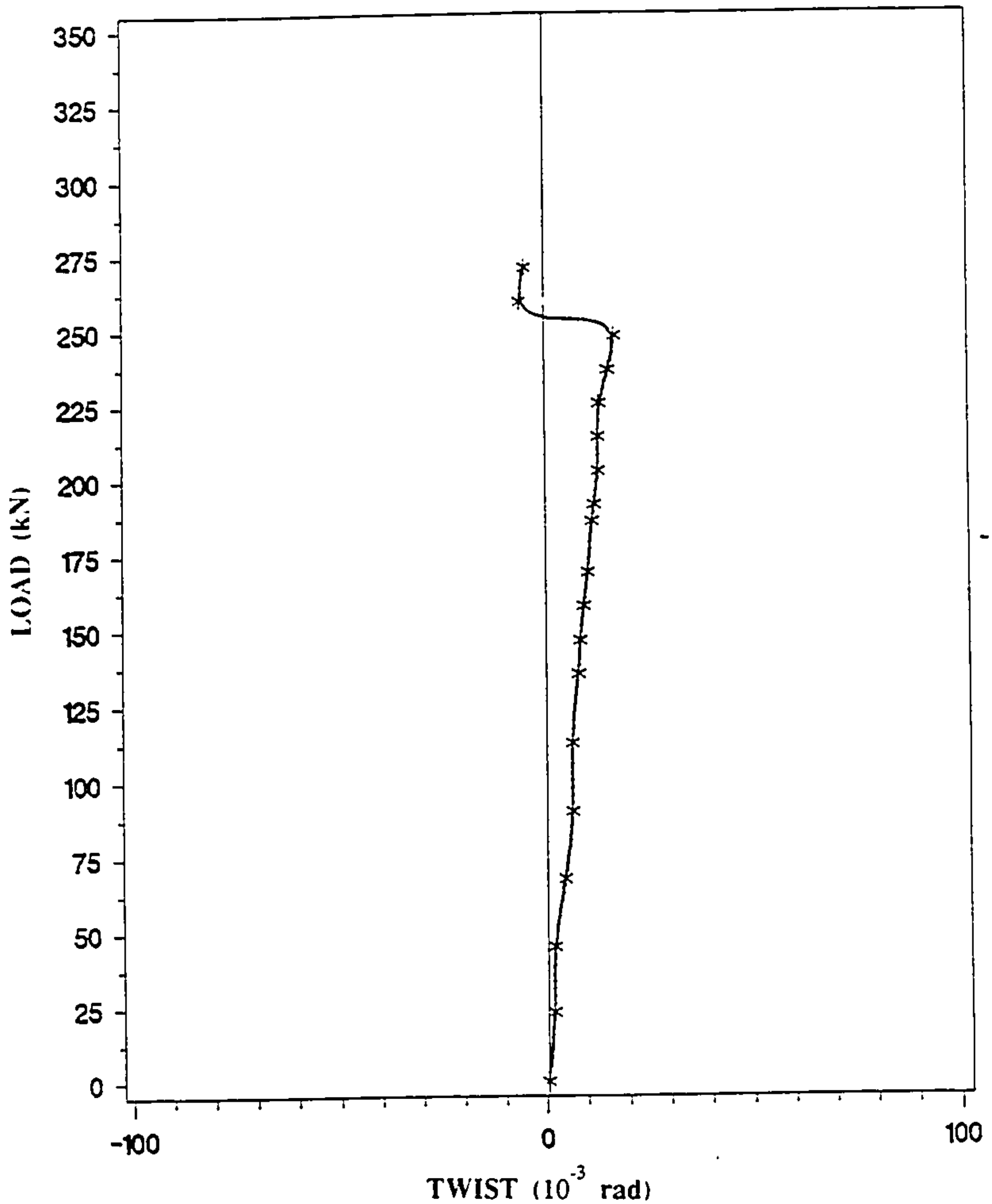


Fig.A.4c

LOAD vs MID-HEIGHT TWIST, SPECIMEN S4 - 1/4 - 1

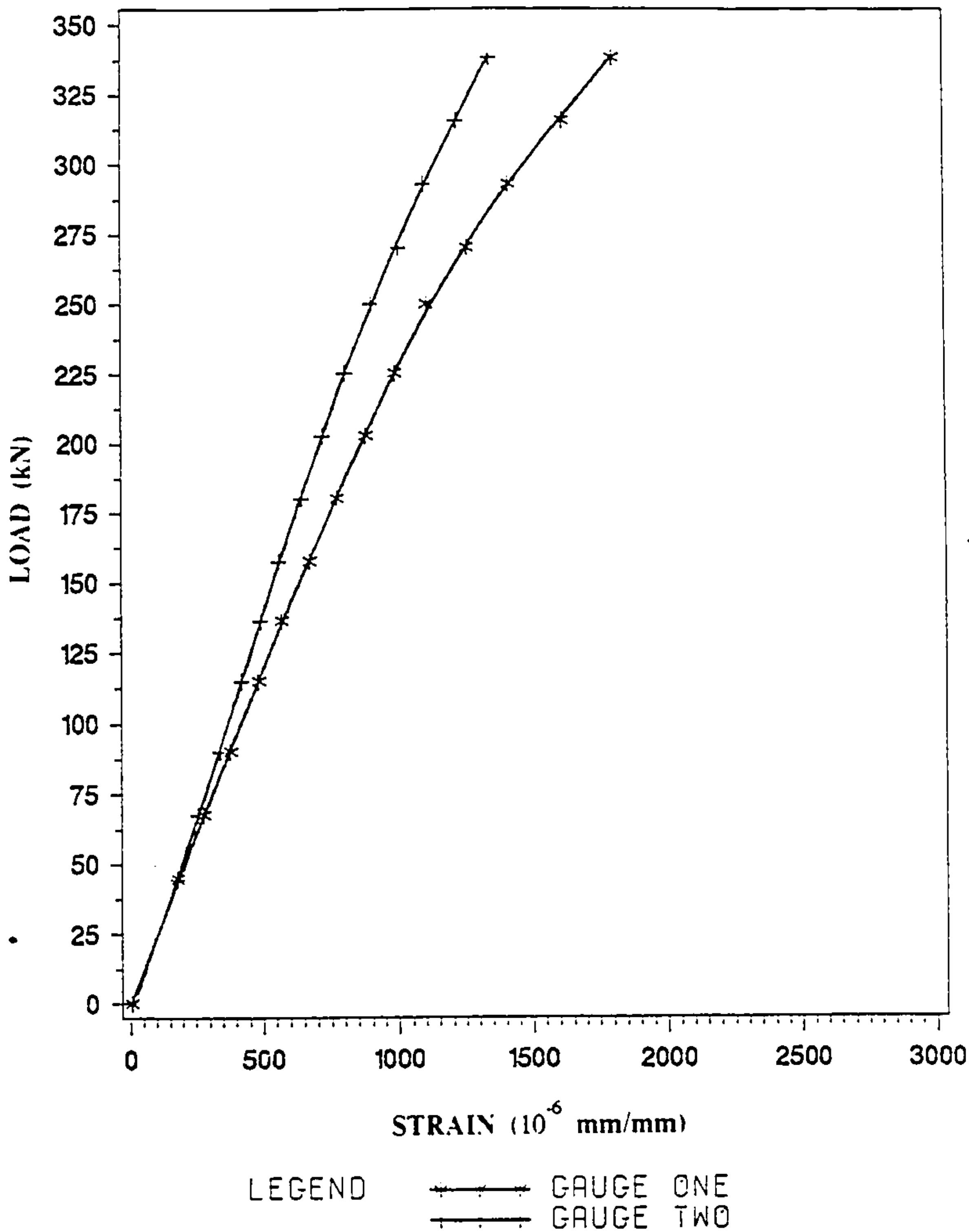
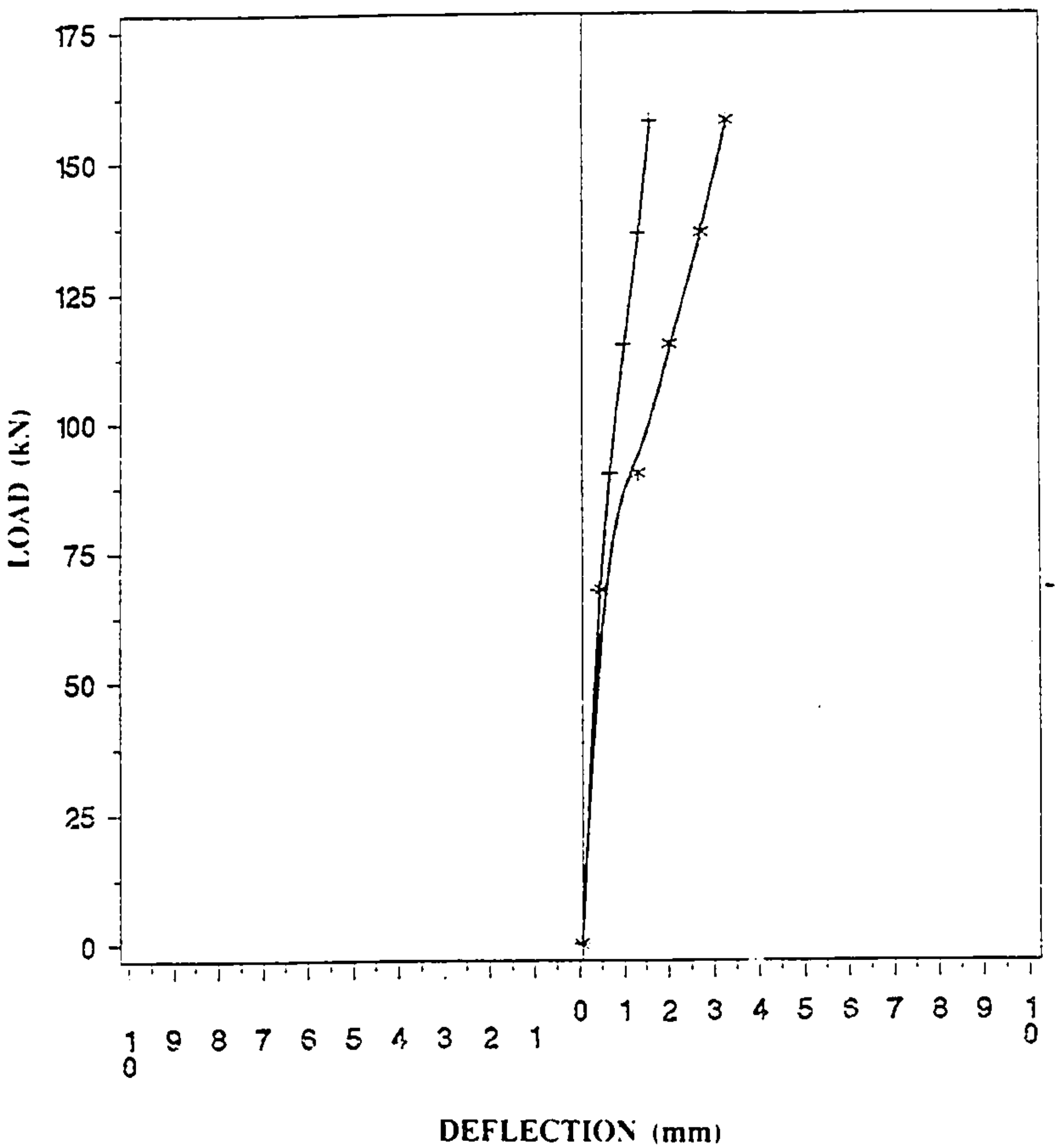


Fig.A.5a

LOAD vs SURFACE STRAIN, SPECIMEN S5 - 5/16 - 1



LEGEND
x x x U-U DEFLECTION
+ + + V-V DEFLECTION

Fig.A.5b

LOAD vs DEFLECTION, SPECIMEN S5 - 5/16 - 1

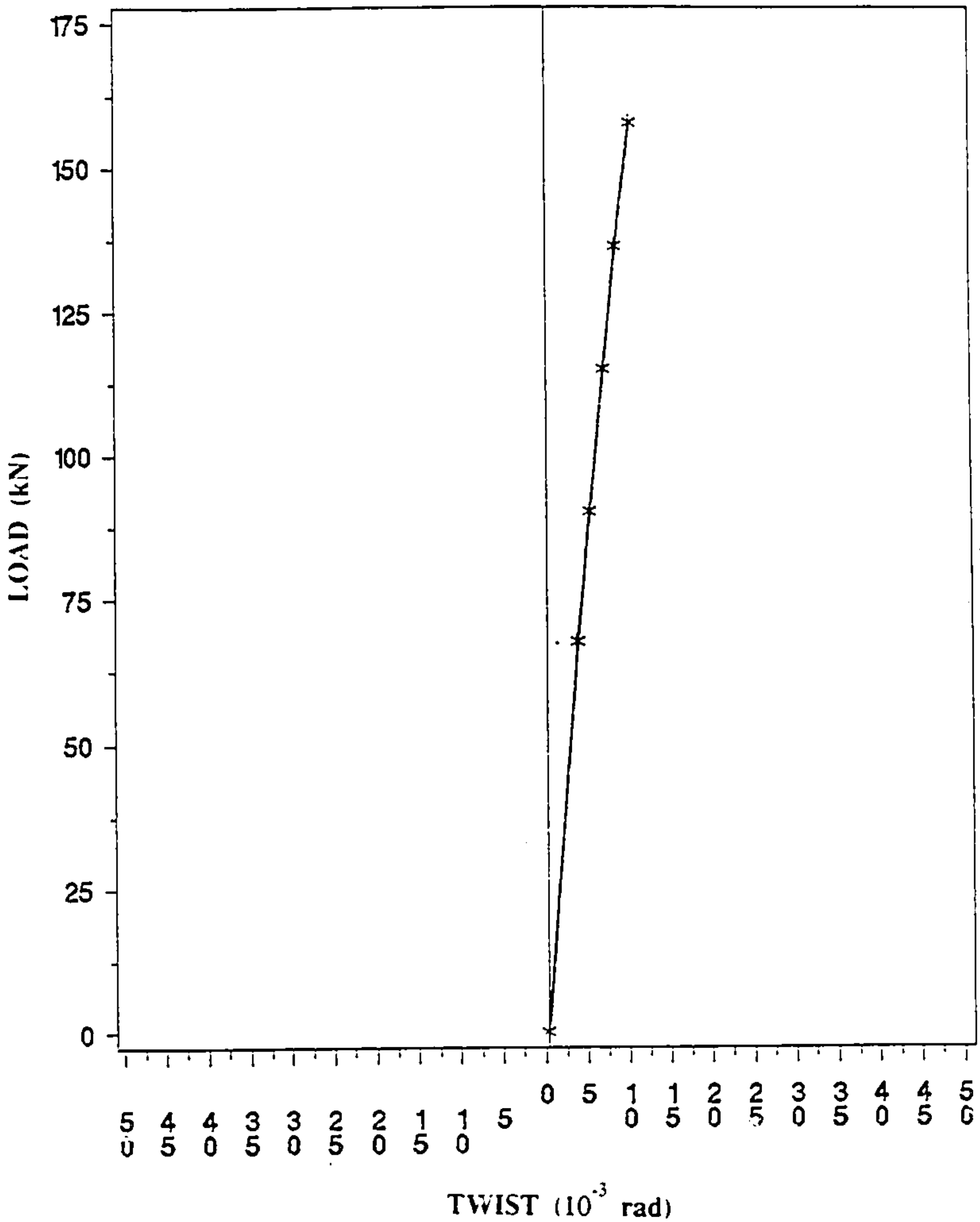


Fig.A.5c

LOAD vs MID-HEIGHT TWIST, SPECIMEN S5 - 5/16 - 1

Appendix B
COMPUTER PROGRAM TO CALCULATE CROSS-SECTIONAL PROPERTIES OF SCHIFFLERIZED ANGLES

```
**********************************************************************
**      PROGRAM TO COMPUTE SECTION PROPERTIES FOR 45-DEG. SCHIFFLERISED *
**       HOT-ROLLED ANGLES.                                             *
**       W=NOMINAL LEG WIDTH , T=NOMINAL LEG THICKNESS                  *
**       A=NOMINAL WIDTH OF UNSCHIFFLERISED STRAIGHT PORTION            *
**       RHO= ROOT RADIUS OF THE ANGLE                                  *
**       AL=EFFECTIVE LENGTH OF THE MEMBER                              *
**       THETA=ANGLE OF SCHIFFLERISATION = 15 DEGREES                   *
**                                                                      *
**********************************************************************
CC      FOR EXPLANATIONS, SEE PROGRAM IN APPENDIX C
        PROGRAM PROPTY
        REAL SLAM,SLAM2,SLAMR,SLAMDAE
        CHARACTER*12 SPECI
        CHARACTER*20 PP(40)
        DIMENSION COOR(500,3),WD(20),TD(20),AD(20),ALD(20),NJ(9)
        DIMENSION ASCE(8),AISC(8),CSA(8),BS(8,2),ECCS(8,2),S(40,40)
C       DIMENSION WBRITISH(13,3),TBRITISH(13),ABRITISH(13)
C       DIMENSION WSIUNITS(13,3),TSIUNITS(13),ASIUNITS(13)
        DATA IIN,IOUT,PI,THETA/5,6,3.141592654,15.0/
C       DATA ((WBRITISH(I,J),J=1,3),I=1,13)/.65,125,1/
        DATA NJ/1,9,17,177,337,169,161,329,321/
        DATA (PP(I),I=1,22)/'Leg width (mm)','a (mm)','b (mm)','t (mm)',
     . 'c (mm)','Area (mm*mm)',
     . 'uc (mm)','I-max 10**6(mm**4)','I-min 10**6(mm**4)',
     . 'I-uc 10**6(mm**4)',
     . 'J 10**4(mm**4)','C-w 10**0(mm**6)','R-u (mm)',
     . 'R-v (mm)','R-q (mm)',
     . 'R-o (mm)','Length (mm)',
     . 'Slenderness kL/r','Non.Dim. kL/r','Yield stress MPa',
     . 'Young''s Mod. GPa','Ult.Load kN'/
**
C       THETA=45.
C       THETA=0.0    ! TEST CASE FOR REGULAR ANGLES
C       E=29.0E+06
C       G=E/2.6
        DO 10 I=1,500
        DO 10 J=1,3
   10   COOR(I,J)=0.0
        THETA=PI*THETA/180.0
        READ(IIN,*)N,E,AMU,AL
        G=E/(2.0*(1.0+AMU))
        DO 2000 NMEM=1,N
        READ(IIN,*)W,T,A,YIELD,RHO1,PTEST,SPECI
        PTEST=PTEST*1000.
C       RHO=T
        B=W-A
        AT=A-T/2.0
        AREA=2.0*T*(AT+B)
        UC=(AT*AT+2.0*B*(AT+0.5*B*(COS(THETA)+SIN(THETA))))/(4.0*(AT+B))
```

```
      ZCEXC I.E.CENTROIDAL COORDINATES
**    COORDINATES OF THE MAIN POINTS, IN THE F.E.M. MODEL
      COOR(1,2)=AT+B*COS(THETA)
      COOR(1,3)=B*SIN(THETA)
      COOR(9,2)=AT
      COOR(9,3)=0.0
      COOR(17,2)=0.0
      COOR(17,3)=0.0
      COOR(177,2)=0.0
      COOR(177,3)=AT                  !
      COOR(337,2)=B*SIN(THETA)        !          5*    8          9
      COOR(337,3)=AT+B*COS(THETA)     !
      COOR(169,2)=XC                  !          *                7
      COOR(169,3)=YC                  !
      COOR(161,2)=AT+B*COS(THETA)     !         *                 *1
      COOR(161,3)=YC+B*SIN(THETA)     !                         *
      COOR(329,2)=XC+B*SIN(THETA)     !        *             *
      COOR(329,3)=AT+B*COS(THETA)     !      4*    6       *
      COOR(321,2)=AT+B*COS(THETA)     !       *          *
      COOR(321,3)=AT+B*COS(THETA)     !        ******
**                                    !      3      2
      DO 100 I=1,9
      J=NJ(I)
      X=(COOR(J,2)+COOR(J,3))/SQRT(2.0)
      Y=(COOR(J,3)-COOR(J,2))/SQRT(2.0)
      COOR(J,2)=X
      COOR(J,3)=Y
100   CONTINUE
**    MOMENTS OF INERTIA
      AIX2=B*T*T*T/12.0
      AIY2=T*B*B*B/12.0
      AI1X=AIX2*COS(THETA)*COS(THETA)+AIY2*SIN(THETA)*SIN(THETA)
      AIY1=AIY2*COS(THETA)*COS(THETA)+AIX2*SIN(THETA)*SIN(THETA)
      AI1XY1=(AIY2-AIX2)*SIN(2.0*THETA)/2.0
      AIX=AI1X+B*T*(B*SIN(THETA)/2.0)**2
      AIY=AIY1+B*T*(AT+B*COS(THETA)/2.0)**2
      AIYO=AIY+AIX+T*AT*AT*AT/3.0+AT*T*T*T/12.0
      AIXO=AIYO
      AIXYO=2.0*(AI1XY1+B*T*B*SIN(THETA)/2.*(AT+0.5*B*COS(THETA)))
**    M.I. ABOUT CENTROIDAL AXIS
      AIXC=AIXO-AREA*XC*XC
      AIYC=AIYO-AREA*YC*YC
      AIXYC=AIXYO-AREA*XC*YC
      AII=SQRT(((AIYC-AIXC)**2)/4.0+AIXYC**2)
      AIMAX=(AIXC+AIYC)/2.0+AII
      AIMIN=(AIXC+AIYC)/2.0-AII
      YO2=XC*XC+YC*YC
      YO=SQRT(YO2)
CC
      C=A-T/2.0
```

```
      AIMAX=B*T*T*T/16.+[illegible]
      AIMAX=2.*(AIMAX+[illegible]*T*T*T/24.+[illegible])
      YO=(2.*C*C+4.*[illegible]+SQRT(2.)*B*A)/(4.*SQRT(2.)*(B+C))
      YO2=YO*YO
      AIMIN=B*T*(T*T/48.+B*B/16.+(C/SQRT(2.)+B*SQRT(3.)/4.)**2)
      AIMIN=2.*(AIMIN+(C*T*T*T*4.*T*C*C*C)/24.)-YO2*AREA
CC
      AIP=AIMIN+AIMAX+AREA*YO2
      AJ=2.0*(W-T/2.0)*T*T*T/3.0
      GAMA=AREA*AREA*AREA/144.0
      RMIN2=AIMIN/AREA
      RMAX2=AIMAX/AREA
      ALBYR=AL/SQRT(RMIN2)
      RP2=AIP/AREA
      RZMIN=SQRT(RMIN2)
      R=1.0-YO2/RP2
      RPHI2=AL*AL*G*AJ/(PI*PI*E*AIP)+GAMA/AIP
      RE2=(RMAX2+RPHI2-SQRT((RMAX2+RPHI2)**2-4.*R*RMAX2*RPHI2))
      RE2=RE2/(2.0*R)
      RU=SQRT(RMAX2)
      RV=SQRT(RMIN2)
      RPHI=SQRT(RPHI2)
      RE=SQRT(RE2)

      PX=PI*PI*E*AIMIN/(AL*AL)
      PY=PI*PI*E*AIMAX/(AL*AL)
      PE=PI*PI*E*AREA*RE2/(AL*AL)
        fact=(AIMIN+AIMAX)/AIP
      !WRITE(IOUT,1100)W,W,T,rho,yield,a]
 1100 FORMAT(1X,'  actual size',
     . f7.3,'x',f7.3,'x',f6.3/1x,'fillet radius = ',f7.3/'Yield stress
     . ,e9.4,'  LENGTH = ',F).1)
  400 FORMAT('**',I3,',',F16.),',',F16.),',',F16.9)
  500 CONTINUE
      I=NMEM
      S(I,1)=W
      S(I,2)=A
      S(I,3)=B
      S(I,4)=T
      S(I,5)=RHO
      S(I,6)=AREA
      S(I,7)=YO
      S(I,8)=AIMAX/10**6
      S(I,9)=AIMIN/10**6
      S(I,10)=AIP/10**6
      S(I,11)=AJ/10**4
      S(I,12)=GAMA/10**8
      S(I,13)=RU
      S(I,14)=RV
      S(I,15)=RPHI
```

```
      S(I,16)=RI
      S(I,17)=AL
      S(I,18)=AL/RV
      S(I,19)=AL/(RV*PI)*SQRT(YIELD/E)
      S(I,20)=YIELD
      S(I,21)=E/1000.
      S(I,22)=FTEST/1000.

2000  CONTINUE
      WRITE(IOUT,3020)
3020  FORMAT(28X,'TABLE 5.1'/4X,'PROPERTIES OF TEST SPECIMENS',
    . ',NOMINAL SIZE : 5x5x5/16 in.'/'PROPERTY',14X,'NOMINAL',
    . '    SECTION-1    SECTION-2    SECTION-3'/65('-'))

      DO 3010 J=1,7
3010  WRITE(IOUT,3000)PP(J),(S(I,J),I=1,4)
      DO 3050 J=8,12
3050  WRITE(IOUT,3030)PP(J),(S(I,J),I=1,4)
      DO 3040 J=13,17
3040  WRITE(IOUT,3000)PP(J),(S(I,J),I=1,4)
      WRITE(IOUT,3060)
3060  FORMAT(65('-')/'** For explanations ref. Fig.1.6 and NOTATION')
3030  FORMAT(/A19,1X,4(F9.3,3X))
3000  FORMAT(/A19,1X,4(F9.1,3X))
      STOP
      END
```

Appendix C

COMPUTER PROGRAM TO CALCULATE ULTIMATE LOADS ACCORDING TO DIFFERENT STANDARD SPECIFICATIONS

```
**************************************************************
**     PROGRAM TO COMPUTE ULTIMATE STRENGTHS AS PER VARIOUS CODES  *
**      HOT-ROLLED SCHIFFLERIZED ANGLES UNDER CONCENTRIC LOAD      *
**      FLEXURAL AND TORSIONAL-FLEXURAL BUCKLING LOADS             *
**      W=LEG WIDTH , T=LEG THICKNESS                              *
**      A=NOMINAL WIDTH OF UNSCHIFFLERISED STRAIGHT PORTION        *
**      RHO=ROOT RADIUS OF THE ANGLE                               *
**      AL=EFFECTIVE LENGTH OF THE MEMBER                          *
**      THETA=ANGLE OF SCHIFFLERISATION = 15 DEGREES               *
**      CODES=TAG FOR DIFFERENT STANDARD SPECIFICATIONS            *
**      SLAM*=SLENDERNESS RATIOS FOR DIFFERENT CASES               *
**************************************************************

        PROGRAM PROPTY
        REAL SLAM,SLAM2,SLAMR,SLAMDAE
        CHARACTER*12 SPECI
        CHARACTER*20 CODES(10),CODE,NOMINAL(2)
        DIMENSION COOR(500,3),WD(20),TD(20),AD(20),ALD(20),NJ(9)
        DIMENSION ASCE(8),AISC(8),CSA(8),BS(8),ECCS(8),FACTR(40)
        DATA IIN,IOUT,PI,THETA/5,6,3.141592654,15.0/
        DATA NJ/1,9,17,177,337,169,161,329,321/
        DATA CODES(1)/'CAN/CSA-S37-M86'/
        DATA CODES(2)/'ASCE-MANUAL 52-1988'/
        DATA CODES(3)/'AISC-LRFD-1986'/
        DATA CODES(4)/'BS 5960:PART 1:1985'/
        DATA CODES(5)/'ECCS - 1985'/
        DATA CODES(6)/'BS 5960:PART 1:1985'/
        DATA CODES(7)/'ECCS - 1985'/
        DATA NOMINAL/'actual ','nominal'/

C       THETA=0.0   ! TEST CASE FOR REGULAR ANGLES
**
        DO 10 I=1,500
        DO 10 J=1,3
   10   COOR(I,J)=0.0
        THETA=PI*THETA/180.0
**
        READ(IIN,*)N,E,AMU,AL,PHI,KODE,KNOMINA,ITABLE
**      N=NO. OF MEMBERS
**      E=YOUNG'S MODULUS
**      AMU=POISSON'S RATIO
**      AL=LENGTH OF MEMBERS
**      KODE=SPECIFICATION NUMBER (IN THE ORDER OF DATA STATEMENT)
**      ITABLE=TABLE NUMBER IN THE HEADING
        IF(KNOMINA.EQ.2)READ(IIN,20)
   20   FORMAT(17(/))
        CODE=CODES(KODE)
        WRITE(IOUT,3070)ITABLE,CODE,NOMINAL(KNOMINA),PHI
**
        G=E/(2.0*(1.0+AMU))
```

```
**      SHEAR MODULUS
C       READ(IIN,*)(FACTR(II),II=1,N)
**
**
        DO 2000 NMEM=1,N
**
        READ(IIN,*)W,T,A,YIELD,RHO,PTEST,SPECI
**      YIELD=YIELD STRESS OF THE MATERIAL
**      RHO=ROOT RADIUS OF THE ANGLE
**      PTEST=EXPERIMENTAL FAILURE LOAD
**      SPECI=SPECIMEN NAME
**
        PTEST=PTEST*1000.
        B=W-A
        AT=A-T/2.0
        AREA=2.0*T*(AT+B)
        XC=(AT*AT+2.0*B*(AT+0.5*B*(COS(THETA)+SIN(THETA))))/(4.0*(AT+B))
        YC=XC ! CENTROIDAL COORDINATES
**      MOMENTS OF INERTIA
        AIX2=B*T*T*T/12.0
        AIY2=T*B*B*B/12.0
        AI1X=AIX2*COS(THETA)*COS(THETA)+AIY2*SIN(THETA)*SIN([illegible]
        AIY1=AIY2*COS(THETA)*COS(THETA)+AIX2*SIN(THETA)*S[illegible]
        AI1XY1=(AIY2-AIX2)*SIN(2.0*THETA)/2.0
        AIX=AI1X+B*T*(B*SIN(THETA)/2.0)**2
        AIY=AIY1+B*T*(AT+B*COS(THETA)/2.0)**2
        AIYO=AIY+AIX+T*AT*AT*AT/3.0+AT*T*T*T/12.0
        AIXO=AIYO
        AIXYO=2.0*(AI1XY1+B*T*B*SIN(THETA)/2.*(AT+0.5*B*COS(THETA)))
**      M.I. ABOUT CENTROIDAL AXIS
        AIXC=AIXO-AREA*XC*XC
        AIYC=AIYO-AREA*YC*YC
        AIXYC=AIXYO-AREA*XC*YC
        AII=SQRT(((AIYC-AIXC)**2)/4.0+AIXYC**2)
        AIMAX=(AIXC+AIYC)/2.0+AII
        AIMIN=(AIXC+AIYC)/2.0-AII
        YO2=XC*XC+YC*YC
        YO=SQRT(YO2)
CC
        C=A-T/2.0
        AIMAX=B*T*T*T/16.+B*B*B*T/48.+B*T*(B/4.+C/SQRT(2.))**2
        AIMAX=2.*(AIMAX+C*T*T*T/24.0+T*C*C*C/6.0)
        YO=(2.*C*C+4.*B*C+SQRT(6.)*B*B)/(4.*SQRT(2.)*(B+C))
        YO2=YO*YO
        AIMIN=B*T*(T*T/48.+B*B/16.+(C/SQRT(2.)+B*SQRT(3.)/4.)**2)
        AIMIN=2.*(AIMIN+(C*T*T*T+4.*T*C*C*C)/24.)-YO2*AREA
CC
**      AIP=POLAR MOMENT OF INERTIA
        AIP=AIMIN+AIMAX+AREA*YO2
**      AIJ=ST. VENANT'S TORSIONAL CONSTANT
```

```
        AJ=2.0*(W-T/2.0)*T*T*T/3.0
**      GAMA=WARPING CONSTANT
        GAMA=AREA*AREA*AREA/144.0
**      RMIN2= SQUARE OF MINIMUM RADIUS OF GYRATION
        RMIN2=AIMIN/AREA
**      RMAX2= SQUARE OF MAXIMUM RADIUS OF GYRATION
        RMAX2=AIMAX/AREA
**      ALBYR=SLENDERNESS RATIO
        ALBYR=AL/SQRT(RMIN2)
        RP2=AIP/AREA
        RZMIN=SQRT(RMIN2)
**      R=SHAPE FACTOR
        R=1.0-YO2/RP2
**      RPHI2=SQUARE OF RADIUS OF GYRATION IN TORSIONAL MODE
        RPHI2=AL*AL*G*AJ/(PI*PI*E*AIP)+GAMA/AIP
**      RE=EQUIVALENT RADIUS OF GYRATION IN TORSIONAL-FLEXURAL MODE
        RE2=(RMAX2+RPHI2-SQRT((RMAX2+RPHI2)**2-4.*R*RMAX2*RPHI2))
        RE2=RE2/(2.0*R)
        RU=SQRT(RMAX2)
        RV=SQRT(RMIN2)
        RPHI=SQRT(RPHI2)
        RE=SQRT(RE2)
**
**      PX=CRITICAL BUCKLING LOAD ABOUT MINOR AXIS
**      PY=CRITICAL LOAD - BUCKLING ABOUT MAJOR AXIS
**      PE=CRITICAL LOAD - BUCKLING ABOUT MINOR AXIS
        PX=PI*PI*E*AIMIN/(AL*AL)
        PY=PI*PI*E*AIMAX/(AL*AL)
        PE=PI*PI*E*AREA*RE2/(AL*AL)
          fact=(AIMIN+AIMAX)/AIP
        !WRITE(IOUT,1100)W,W,T,rho,yield,al
1100    FORMAT(1X,'  actual size',
      . f7.3,'x',f7.3,'x',f6.3/1X,'fillet radius = ',f7.3/'Yield stress'
      . ,e9.4,'  LENGTH = ',F9.3)

        Fy=YIELD
**      SLAM=NON-DIMENSIONAL COLUMN SLENDERNESS PARAMETER
        SLAM=AL*SQRT(Fy/(PI*PI*E*RMIN2))
        SLAM2=SLAM*SLAM
**
C       PHI=1.0
**      CAN3-S16.1-M84 CLAUSE 13.3.1
**      PHI=RESISTANCE FACTOR
        Cr=PHI*AREA*Fy
        IF(0.0.LE.SLAM.AND.SLAM.LE.0.15)Cr=Cr
        IF(.15..T.SLAM.AND.SLAM.LE.1.)Cr=Cr*(1.035-.202*SLAM-.222*SLAM2)
        IF(1..LT.SLAM.AND.SLAM.LE.2.)Cr=Cr*(-.111+.636/SLAM+.087/SLAM2)
        IF(2.0.LT.SLAM.AND.SLAM.LE.3.6)Cr=Cr*(0.009+0.877/SLAM2)
        IF(3.6.LE.SLAM)Cr=Cr/SLAM2
        !WRITE(IOUT,120)Cr
```

```
FILE: C1       FORTRAN  A1  UNIVERSITY OF WINDSOR                                    PAGE 00004

 1200  FORMAT(5X,'CAN3-S16.1-M84 CLAUSE 11.3.1  Cr= ',F12.5)
 **    PROPOSED REVISION FOR CSA S37-M86 PARAGRAPH 6.2.)
       WB=W-A
       IF(WB/T.LE.200/SQRT(YIELD)) THEN
       Fcr=YIELD
       ELSE IF(WB/T.LE.380/SQRT(YIELD)) THEN
       Fcr=YIELD*(1.677-0.677*(WB/T)/(200/SQRT(YIELD)))
       ELSE
       Fcr=56415/(WB/T)**2
       END IF
       SLAM=AL*SQRT(Fcr/(PI*PI*E*RMIN2))
       SLAM2=SLAM*SLAM
       Cr=PHI*AREA*Fcr
       IF(0.0.LE.SLAM.AND.SLAM.LE.0.15)Cr=Cr
       IF(.15.LT.SLAM.AND.SLAM.LE.1.)Cr=Cr*(1.035-.202*SLAM-.222*SLAM2)
       IF(1..LT.SLAM.AND.SLAM.LE.2.)Cr=Cr*(-.111+.636/SLAM+.087/SLAM2)
       IF(2.0.LT.SLAM.AND.SLAM.LE.3.6)Cr=Cr*(0.009+0.877/SLAM2)
       IF(3.6.LE.SLAM)Cr=Cr/SLAM2
       CSA(1)=CR
       CSA(2)=PTEST/CR
       !WRITE(IOUT,1300)WB,Cr
 1300  FORMAT(5X,'CSA-S37-M86 REV. BEND WIDTH w = ',F7.3,'[redacted]12.5)
 **
 **
       WB=W-RHO-T
       IF(WB/T.LE.200/SQRT(YIELD)) THEN
       Fcr=YIELD
       ELSE IF(WB/T.LE.380/SQRT(YIELD)) THEN
       Fcr=YIELD*(1.677-0.677*(WB/T)/(200/SQRT(YIELD)))
       ELSE
       Fcr=56415/(WB/T)**2
       END IF
       SLAM=AL*SQRT(Fcr/(PI*PI*E*RMIN2))
       SLAM2=SLAM*SLAM
       Cr=PHI*AREA*Fcr
       IF(0.0.LE.SLAM.AND.SLAM.LE.0.15)Cr=Cr
       IF(.15.LT.SLAM.AND.SLAM.LE.1.)Cr=Cr*(1.035-.202*SLAM-.222*SLAM2)
       IF(1..LT.SLAM.AND.SLAM.LE.2.)Cr=Cr*(-.111+.636/SLAM+.087/SLAM2)
       IF(2.0.LT.SLAM.AND.SLAM.LE.3.6)Cr=Cr*(0.009+0.877/SLAM2)
       IF(3.6.LE.SLAM)Cr=Cr/SLAM2
       CSA(3)=CR
       CSA(4)=PTEST/CR
       !WRITE(IOUT,1400)W,Cr
 1400  FORMAT(5X,'CSA-S37-M86 REV.FILLET WIDTH w = ',F7.3,' Cr= ',E12.5)
 **
 **
       WB=W-T
       IF(WB/T.LE.200/SQRT(YIELD)) THEN
       Fcr=YIELD
       ELSE IF(WB/T.LE.380/SQRT(YIELD)) THEN
```

```
      Fcr=YIELD*(1.677-0.677*(WB/T)/(200/SQRT(YIELD)))
      ELSE
      Fcr=56415/(WB/T)**2
      END IF
      SLAM=AL*SQRT(Fcr/(PI*PI*E*RMIN2))
      SLAM2=SLAM*SLAM
      Cr=PHI*AREA*Fcr
      IF(0.0.LE.SLAM.AND.SLAM.LE.0.15)Cr=Cr
      IF(.15.LT.SLAM.AND.SLAM.LE.1.)Cr=Cr*(1.035-.202*SLAM-.222*SLAM2)
      IF(1..LT.SLAM.AND.SLAM.LE.2.)Cr=Cr*(-.111+.636/SLAM+.087/SLAM2)
      IF(2.0.LT.SLAM.AND.SLAM.LE.3.6)Cr=Cr*(0.009+0.877/SLAM2)
      IF(3.6.LE.SLAM)Cr=Cr/SLAM2
      CSA(5)=CR
      CSA(6)=PTEST/CR
      !WRITE(IOUT,1450)w,Cr
 1450 FORMAT(5X,'CSA-S37-M86 REV. a+b-t/w = ',F7.3,' Cr= ',E12.5)
**
**
      WB=W
      IF(WB/T.LE.200/SQRT(YIELD)) THEN
      Fcr=YIELD
      ELSE IF(WB/T.LE.380/SQRT(YIELD)) THEN
      Fcr=YIELD*(1.677-0.677*(WB/T)/(200/SQRT(YIELD)))
      ELSE
      Fcr=56415/(WB/T)**2
      END IF
      SLAM=AL*SQRT(Fcr/(PI*PI*E*RMIN2))
      SLAM2=SLAM*SLAM
      Cr=PHI*AREA*Fcr
      IF(0.0.LE.SLAM.AND.SLAM.LE.0.15)Cr=Cr
      IF(.15.LT.SLAM.AND.SLAM.LE.1.)Cr=Cr*(1.035-.202*SLAM-.222*SLAM2)
      IF(1..LT.SLAM.AND.SLAM.LE.2.)Cr=Cr*(-.111+.636/SLAM+.087/SLAM2)
      IF(2.0.LT.SLAM.AND.SLAM.LE.3.6)Cr=Cr*(0.009+0.877/SLAM2)
      IF(3.6.LE.SLAM)Cr=Cr/SLAM2
      CSA(7)=CR
      CSA(8)=PTEST/CR
      !WRITE(IOUT,1500)Cr
 1500 FORMAT(5X,'CSA-S37-M86 REVISION W=NOMINAL LEG WIDTH,Cr= ',E12.5)
**
**
**
**    AISC - LRFD 1986
C     PHI=1.0
      SLAMR=76./SQRT(YIELD/6.894757)
      WB=W-A
      WBYT=WB/T
      IF(WBYT.LT.SLAMR) THEN
      Q=1.0
      ELSE IF(SLAMR.LE.WBYT.AND.WBYT.LT.155*SLAMR/76) THEN
      Q=1.340-0.00447*WBYT*SQRT(YIELD/6.894757)
```

```
        ELSE
        Q=15500/(YIELD*WBYT*WBYT/6.894757)
        ENDIF
        Fy=YIELD/6.894757
        SLAM=AL*SQRT(Fy*6.894757/(PI*PI*E))/SQRT(RMIN2)
        SLAM2=SLAM*SLAM
        IF(SLAM.LE.1.5)Fcr=(0.658**(SLAM2*Q))*Fy*Q
        IF(SLAM.GT.1.5)Fcr=0.877*Fy/SLAM2
        Pne=PHI*AREA*Fcr
        SLAMBDAE=SQRT(AREA*YIELD/PE)
        SLAMQ=SLAMBDAE*SQRT(Q)
        IF(SLAMQ.LE.1.5)Fcr=(0.658**(SLAMQ*SLAMQ))*Fy*Q
        IF(SLAMQ.GT.1.5)Fcr=0.877*Fy*Q/(SLAMQ*SLAMQ)
        Pnphi=PHI*AREA*Fcr
C       !WRITE(IOUT,*)SLAM,WBYT,SLAMBDAE,FCR
        Cr=6.894757*AMIN1(Pne,Pnphi)
        AISC(1)=CR
        AISC(2)=PTEST/CR
        !WRITE(IOUT,1600)WB,Cr,PNE,PNPHI
 1600   FORMAT(1X,'AISC-LRFD1986 PLAT W=',F7.3,' CR=',E12.4,E12.4,F12.4)
**
**
C       PHI=1.0
        SLAMR=76./SQRT(YIELD/6.894757)
        WB=W-T-RHO
        WBYT=WB/T
        IF(WBYT.LT.SLAMR) THEN
        Q=1.0
        ELSE IF(SLAMR.LE.WBYT.AND.WBYT.LT.155*SLAMR/76) THEN
        Q=1.340-0.00447*WBYT*SQRT(YIELD/6.894757)
        ELSE
        Q=15500/(YIELD*WBYT*WBYT/6.894757)
        ENDIF
        Fy=YIELD/6.894757
        SLAM=AL*SQRT(Fy*6.894757/(PI*PI*E*RMIN2))
        SLAM2=SLAM*SLAM
        IF(WB/T.LE.76/SQRT(FY)) THEN
        IF(SLAM.LE.1.5)Fcr=(0.658**SLAM2)*Fy
        IF(SLAM.GT.1.5)Fcr=0.877*Fy/SLAM2
        ELSE IF(SLAM.LE.1.5) THEN
        FCR=(0.658**(SLAM2*Q))*Q*FY
        ELSE
        FCR=(0.877*FY)/SLAM2
        ENDIF
        Pne=PHI*AREA*Fcr
        SLAMBDAE=SQRT(AREA*YIELD/PE)
        SLAMQ=SLAMBDAE*SQRT(Q)
        IF(SLAMQ.LE.1.5)Fcr=(0.658**(SLAMQ*SLAMQ))*Fy*Q
        IF(SLAMQ.GT.1.5)Fcr=0.877*Fy*Q/(SLAMQ*SLAMQ)
        Pnphi=PHI*AREA*Fcr
```

```
      Cr=6.894757*AMIN1(Pne,Pnphi)
      AISC(3)=CR
      AISC(4)=PTEST/CR
      WRITE(IOUT,1600)WB,Cr,PNE,PNPHI
1610  FORMAT(1X,'AISC-LRFD1986 FLAT W=',F7.3,' CR=',E12.4,E12.4,E12.4)
**
**
C     PHI=1.0
      SLAMR=76./SQRT(YIELD/6.894757)
      WB=W-T
      WBYT=WB/T
      IF(WBYT.LT.SLAMR) THEN
      Q=1.0
      ELSE IF(SLAMR.LE.WBYT.AND.WBYT.LT.155*SLAMR/76) THEN
      Q=1.340-0.00447*WBYT*SQRT(YIELD/6.894757)
      ELSE
      Q=15500/(YIELD*WBYT*WBYT/6.894757)
      ENDIF
      Fy=YIELD*Q/6.894757
      SLAM=AL*SQRT(Fy*6.894757/(PI*PI*E*RMIN2))
      SLAM2=SLAM*SLAM
      IF(SLAM.LE.1.5)Fcr=(0.658**SLAM2)*Fy
      IF(SLAM.GT.1.5)Fcr=0.877*Fy/SLAM2
      Pne=PHI*AREA*Fcr
      SLAMBDAE=SQRT(AREA*YIELD/PE)
      SLAMQ=SLAMBDAE*SQRT(Q)
      IF(SLAMQ.LE.1.5)Fcr=(0.658**(SLAMQ*SLAMQ))*Fy
      IF(SLAMQ.GT.1.5)Fcr=0.877*Fy/(SLAMQ*SLAMQ)
      Pnphi=PHI*AREA*Fcr
      Cr=6.894757*AMIN1(Pne,Pnphi)
      AISC(5)=CR
      AISC(6)=PTEST/CR
      WRITE(IOUT,1620)WB,Cr,PNE,PNPHI
1620  FORMAT(1X,'AISC-LRFD1986 FLAT W=',F7.3,' CR=',E12.4,E12.4,E12.4)
**
**
C     PHI=1.0
      SLAMR=76./SQRT(YIELD/6.894757)
      WB=W
      WBYT=WB/T
      IF(WBYT.LT.SLAMR) THEN
      Q=1.0
      ELSE IF(SLAMR.LE.WBYT.AND.WBYT.LT.155*SLAMR/76) THEN
      Q=1.340-0.00447*WBYT*SQRT(YIELD/6.894757)
      ELSE
      Q=15500/(YIELD*WBYT*WBYT/6.894757)
      ENDIF
      Fy=YIELD*Q/6.894757
      SLAM=AL*SQRT(Fy*6.894757/(PI*PI*E*RMIN2))
      SLAM2=SLAM*SLAM
```

```
      IF(SLAM.LE.1.5)Fcr=(0.658**SLAM2)*Fy
      IF(SLAM.GT.1.5)Fcr=0.877*Fy/SLAM2
      Pno=PHI*AREA*Fcr
      SLAMBDAE=SQRT(AREA*YIELD/PE)
      SLAMQ=SLAMBDAE*SQRT(Q)
      IF(SLAMQ.LE.1.5)Fcr=(0.658**(SLAMQ*SLAMQ))*Fy
      IF(SLAMQ.GT.1.5)Fcr=0.877*Fy/(SLAMQ*SLAMQ)
      Pnphi=PHI*AREA*Fcr
      Cr=6.894757*AMIN1(Pno,Pnphi)
      AISC(7)=CR
      AISC(8)=PTEST/CR
      !WRITE(IOUT,1630)WB,Cr,PNE,PNPHI
 1630 FORMAT(1X,'AISC-LRFD1986 FLAT W=',F7.3,' CR=',E12.4,E12.4,E12.4)
**
**
**
**    ASCE MANUAL # 52
      Fy=YIELD/6.894757
      WB=H-A
      WBYT=WB/T
      WTLIM=80/SQRT(Fy)
      IF(WBYT.LT.WTLIM) THEN
      FCR=FY
      ELSE IF(WBYT.LE.144/SQRT(FY)) THEN
      FCR=FY*(1.677-0.677*WBYT/WTLIM)
      ELSE
      FCR=9500/WBYT**2
      ENDIF
      Cc=PI*SQRT(2.0*E/6.894757/Fy)
      RMIN=SQRT(RMIN2)/25.4
      IF((AL/25.4/RMIN).LE.Cc)Fa=FCR*(1.0-0.5*(AL/25.4/RMIN/CC)**2)
      IF((AL/25.4/RMIN).GT.CC)FA=286000/(AL/25.4/RMIN)**2
      PCR=FA*AREA*6.894757
      ASCE(1)=PCR
      ASCE(2)=PTEST/PCR
      !WRITE(IOUT,1700)WB,PCR
 1700 FORMAT(1X,'ASCE MANUAL #52 FLAT W = ',F7.3,' PCR = ',E12.4)
**
**
      Fy=YIELD/6.894757
      WB=W-RHO-T
      WBYT=WB/T
      WTLIM=80/SQRT(Fy)
      IF(WBYT.LE.WTLIM) THEN
      FCR=FY
      ELSE IF(WBYT.LE.144/SQRT(FY)) THEN
      FCR=FY*(1.677-0.677*WBYT/WTLIM)
      ELSE
      FCR=9500/WBYT**2
      ENDIF
```

```
      Cc=PI*SQRT(2.0*E/6.894757/Fy)
      RMIN=SQRT(RMIN2)/25.4
      IF((AL/25.4/RMIN).LE.Cc)FA=FCR*(1.0-0.5*(AL/25.4/RMIN/CC)**2)
      IF((AL/25.4/RMIN).GT.CC)FA=286000/(AL/25.4/RMIN)**2
      PCR=FA*AREA*6.894757
      ASCE(3)=PCR
      ASCE(4)=PTEST/PCR
     !WRITE(IOUT,1710)WB,PCR
 1710 FORMAT(1X,'ASCE MANUAL #52 FLAT W = ',F7.3,' PCR = ',F12.4)
**
**
      Fy=YIELD/6.894757
      WB=W-T
      WBYT=WB/T
      WTLIM=80/SQRT(Fy)
      IF(WBYT.LT.WTLIM) THEN
      FCR=FY
      ELSE IF(WBYT.LE.144/SQRT(FY)) THEN
      FCR=FY*(1.677-0.677*WBYT/WTLIM)
      ELSE
      FCR=9500/WBYT**2
      ENDIF
      Cc=PI*SQRT(2.0*E/6.894757/Fy)
      RMIN=SQRT(RMIN2)/25.4
      IF((AL/25.4/RMIN).LE.Cc)FA=FCR*(1.0-0.5*(AL/25.4/RMIN/CC)**2)
      IF((AL/25.4/RMIN).GT.CC)FA=286000/(AL/25.4/RMIN)**2
      PCR=FA*AREA*6.894757
      ASCE(5)=PCR
      ASCE(6)=PTEST/PCR
     !WRITE(IOUT,1720)WB,PCR
 1720 FORMAT(1X,'ASCE MANUAL #52 FLAT W = ',F7.3,' PCR = ',E12.4)
**
**
      Fy=YIELD/6.894757
      WB=W
      WBYT=WB/T
      WTLIM=80/SQRT(Fy)
      IF(WBYT.LT.WTLIM) THEN
      FCR=FY
      ELSE IF(WBYT.LE.144/SQRT(FY)) THEN
      FCR=FY*(1.677-0.677*WBYT/WTLIM)
      ELSE
      FCR=9500/WBYT**2
      ENDIF
      Cc=PI*SQRT(2.0*E/6.894757/Fy)
      RMIN=SQRT(RMIN2)/25.4
      IF((AL/25.4/RMIN).LE.Cc)Fa=FCR*(1.0-0.5*(AL/25.4/RMIN/CC)**2)
      IF((AL/25.4/RMIN).GT.CC)FA=286000/(AL/25.4/RMIN)**2
      PCR=FA*AREA*6.894757
      ASCE(7)= PCR
```

```
      ASCE(8)=PTEST/PCR
      !WRITE(IOUT,1730)WB,PCR
 1730 FORMAT(1X,'ASCE MANUAL #52 FLAT W - ',F7.3,' PCR = ',F12.4)
**
**
**
**    BS 5950 : PART 1 : 1985
      RMIN=SQRT(RMIN2)
      EPSI=SQRT(275/YIELD)
      WB=W-A
      WBYT=WB/T
      WTLIM=11.5*EPSI
      REDUCE=AMIN1(11.0/((WB/T/EPSI)-4.),19./((2.*WB/T/EPSI)-4.))
      REDUCE=AMIN1(1.0,REDUCE)
      SLAM=AL/RMIN
      BS(1)=SLAM
      BS(2)=REDUCE*YIELD
*     !WRITE(IOUT,*)AL,RMIN,SLAM
      !WRITE(IOUT,1800)WBYT,WTLIM,REDUCE,SLAM
 1800 FORMAT(1X,'BS 5950 : PART 1 : 1985'/1X,'B/T ',F7.3,' B/T LIM. ',
     .F7.3,/1X,' REDUCTION FACTOR FOR semi-compact SECTION ',F7.3,
     .' SLENDERNESS SLAMBDA : ',F10.4)
**
**
      EPSI=SQRT(275/YIELD)
      WB=W-T-RHO
      WBYT=WB/T
      WTLIM=11.5*EPSI
      REDUCE=AMIN1(11.0/((WB/T/EPSI)-4),19.0/((2.*WB/T/EPSI)-4))
      REDUCE=AMIN1(1.0,REDUCE)
      SLAM=AL/RMIN
      BS(3)=SLAM
      BS(4)=REDUCE*YIELD
*     !WRITE(IOUT,*)AL,RMIN,SLAM
      !WRITE(IOUT,1810)WBYT,WTLIM,REDUCE,SLAM
 1810 FORMAT(1X,'BS 5950 : PART 1 : 1985'/1X,'B/T ',F7.3,' B/T LIM. ',
     .F7.3,/1X,' REDUCTION FACTOR FOR semi-compact SECTION ',F7.3,
     .' SLENDERNESS SLAMBDA : ',F10.4)
**
**
      EPSI=SQRT(275/YIELD)
      WB=W-T
      WBYT=WB/T
      WTLIM=11.5*EPSI
      REDUCE=AMIN1(11.0/((WB/T/EPSI)-4),19.0/((2.*WB/T/EPSI)-4))
      REDUCE=AMIN1(1.0,REDUCE)
      SLAM=AL/RMIN
      BS(5)=SLAM
      BS(6)=REDUCE*YIELD
*     !WRITE(IOUT,*)AL,RMIN,SLAM
```

```
       !WRITE(IOUT,1820)WBYT,WTLIM,REDUCE,SLAM
 1820  FORMAT(1X,'BS 5950 : PART 1 : 198 '/1X,'B/T ',F7.3,' B/T LIM. ',
     . F7.3,/1X,' REDUCTION FACTOR FOR semi-compact SECTION ',F7.3,
     . ' SLENDERNESS SLAMBDA : ',F10.4)
**
**
       EPSI=SQRT(275/YIELD)
       WB=J
       WBYT=WB/T
       WTLIM=11.5*EPSI
       REDUCE=AMIN1(11.0/((WB/T/EPSI)-4),19.0/(((2.*WB/T/EPSI)-4))
       REDUCE=AMIN1(1.0,REDUCE)
       SLAM=AL/RMIN
       BS(7)=SLAM
       BS(8)=REDUCE*YIELD
*      !WRITE(IOUT,*)AL,RMIN,SLAM
       !WRITE(IOUT,1830)WBYT,WTLIM,REDUCE,SLAM
 1830  FORMAT(1X,'BS 5950 : PART 1 : 1985'/1X,'B/T ',F7.3,' B/T LIM. ',
     . F7.3,/1X,' REDUCTION FACTOR FOR semi-compact SECTION ',F7.3,
     . ' SLENDERNESS SLAMBDA : ',F10.4)
**
**
**
**     ECCS - 1985
       RMIN=SQRT(RMIN2)
       EPSI=SQRT(275/YIELD)
       WB=W-A
       WBYT=WB/T
       WTLIM=260./SQRT(YIELD)
C      WTLIM=200./SQRT(YIELD)
       IF(WBYT.LE.WTLIM)THEN
        FY=YIELD
       ELSE IF(WBYT.LT.4.*WTLIM/3.0) THEN
        FY=YIELD*(2.-WBYT/WTLIM)
       ELSE
        FY=80000/(WBYT*WBYT)
       ENDIF
       ECCS(2)=FY/YIELD
       WB=W-T-RHO
       WBYT=WB/T
       WTLIM=260./SQRT(YIELD)
C      WTLIM=200./SQRT(YIELD)
       IF(WBYT.LE.WTLIM)THEN
        FY=YIELD
       ELSE IF(WBYT.LT.4.*WTLIM/3.0) THEN
        FY=YIELD*(2.-WBYT/WTLIM)
       ELSE
        FY=80000/(WBYT*WBYT)
       ENDIF
       ECCS(4)=FY/YIELD
```

```
      WB=W-T
      WBYT=WB/T
      WTLIM=260./SQRT(YIELD)
C     WTLIM=200./SQRT(YIELD)
      IF(WBYT.LE.WTLIM)THEN
       FY=YIELD
      ELSE IF(WBYT.LT.4.*WTLIM/3.0) THEN
       FY=YIELD*(2.-WBYT/WTLIM)
      ELSE
       FY=80000/(WBYT*WBYT)
      ENDIF
      ECCS(6)=FY/YIELD
      WB=W
      WBYT=WB/T
      WTLIM=260./SQRT(YIELD)
C     WTLIM=200./SQRT(YIELD)
      IF(WBYT.LE.WTLIM)THEN
       FY=YIELD
      ELSE IF(WBYT.LT.4.*WTLIM/3.0) THEN
       FY=YIELD*(2.-WBYT/WTLIM)
      ELSE
       PY=80000/(WBYT*WBYT)
      ENDIF
      ECCS(8)=FY/YIELD

      ECCS(1)=AL*SQRT(FY/(PI*PI*E*RMIN2))
      ECCS(3)=AL*SQRT(FY/(PI*PI*E*RMIN2))
      ECCS(5)=AL*SQRT(FY/(PI*PI*E*RMIN2))
      ECCS(7)=AL*SQRT(FY/(PI*PI*E*RMIN2))
      DO 4010 II=1,7,2
      FY=YIELD*ECCS(II+1)
      ALAM=ECCS(II)
      CALL ECCSV(ALAM,FY,FC,AREA,PP)
      ECCS(II)=PP/1000.
      ECCS(II+1)=ECCS(II)*1000/PTEST
 4010 CONTINUE
      DO 4020 II=1,7,2
      ALAM=BS(II)
      FY=BS(II+1)
      CALL BSV(ALAM,FY,FC,AREA,PP)
      BS(II)=PP/1000.
      BS(II+1)=BS(II)*1000./PTEST
 4020 CONTINUE
      DO 4030 II=1,7,2
      CSA(II)=CSA(II)/1000.
      CSA(II+1)=1/CSA(II+1)
 4030 CONTINUE
      DO 3005 II=1,7,2
      AI.. (II)=AI.. (II)/1000.
      A... (II)-A... (II)/1. .
```

```
      AISC(II+1)=1/AISC(II+1)
      ASCE(II+1)=1/ASCE(II+1)
3005  CONTINUE
3010  FORMAT(25X,'TABLE 5.1'/10X,'COMPARISION OF EXPERIMENTAL FAILURE'
     .,' LOADS'/10X,' AND LOADS CALCULATED ACCORDING TO ',A20//5X,
     .'** note : case (I):c+b; (II):w=a+b-t-r; (III):w=a+b-t;'
     .,' (IV):w=a+b'/////5X,65('-'))
      PTEST1=PTEST/1000.
      IF(KODE.EQ.1)WRITE(IOUT,3020)SPECI,PTEST1,(CSA(II),II=1,8)
      IF(KODE.EQ.2)WRITE(IOUT,3020)SPECI,PTEST1,(ASCE(II),II=1,8)
      IF(KODE.EQ.3)WRITE(IOUT,3020)SPECI,PTEST1,(AISC(II),II=1,8)
3020  FORMAT(/A12,1X,F4.0,4(2X,F4.0,2X,F4.2))
      IF(KODE.EQ.4)WRITE(IOUT,3020)SPECI,PTEST1,(BS(II),II=1,8)
      IF(KODE.EQ.6)WRITE(IOUT,3030)SPECI,YIELD,(BS(II),II=1,8)
      IF(KODE.EQ.5)WRITE(IOUT,3020)SPECI,PTEST1,(ECCS(II),II=1,8)
      IF(KODE.EQ.7)WRITE(IOUT,3030)SPECI,YIELD,(ECCS(II),II=1,8)
3030  FORMAT(/A12,1X,F4.0,4(1X,F5.2,1X,F5.1))
      !WRITE(iout,*)w,t,AIXYC,area,RZMIN
      ALBYR=AL/SQRT(RMIN2)
      ALAM=ALBYR*SQRT(YIELD/E)/PI
      PTEST1=PTEST/AREA
      IF(KODE.GT.10)WRITE(IOUT,3040)SPECI,ALBYR,ALAM,PTEST[illegible]
3040  FORMAT(/A12,3X,F6.0,3X,F6.3,3X,F4.0,3X,F4.0)
      !WRITE(IOUT,*)Y0,aimax,aimin,PX,PE
      !WRITE(IOUT,*)AIXC,AIYC,ALBYR,fact
      DO 500 II=1,3
      JJ=NJ(II)
      !WRITE(IOUT,400)JJ,COOR(JJ,1),COOR(JJ,2),COOR(JJ,3)
 400  FORMAT('**',I3,',',F16.9,',',F16.9,',',F16.9)
 500  CONTINUE
2000  CONTINUE
3070  FORMAT(27X,'TABLE 5.',I2/
     . 13X,'COMPARISION OF EXPERIMENTAL FAILURE LOADS'/
     . 10X,'AND LOADS CALCULATED ACCORDING TO ',A20/
     . 11X,'Strength based on ',A7,' dimensions, PHI=',F4.2//'SPECIMEN'
     .,'     P    CASE  CASE  CASE  CASE  CASE  CASE  CASE  CASE'
     ./13X,'TEST    I     I     II    II    III   III   IV    IV'/
     . 13X,'LOAD RATIO  LOAD RATIO  LOAD RATIO  LOAD RATIO'/
     . 13X,'(kN)  (kN)        (kN)        (kN)        (kN)'/
     . 65('-'))
      WRITE(IOUT,3080)
3080  FORMAT(65('-')/'** note : case (I):w=b;',1X,
     .'(II):w=a+b-t-r; (III):w=a+b-t; (IV):w=a+b'/
     .'** See Fig.1.6 for notation; ',
     .' RATIO=''Load P as per code''/''P Test'' ')
      STOP
      END
```

```
      BLOCK DATA
      DIMENSION BST(16,100),BSLAM(100),BSPY(16),ECCSL(300),ECCST(300)
      COMMON/CODETAB/BST,BSLAM,BSPY,ECCSL,ECCST,NXBS,NYBS,NECCS
      DATA NXBS,NYBS,NECCS/16,26,110/
      DATA (BSLAM(I),I=1,26)/50,52,54,56,58,60,62,64,66,68,70,72,
     . 74,76,78,80,82,84,86,88,90,92,94,96,98,100/
      DATA (BSPY(I),I=1,16)/225,245,255,265,275,305,120,325,
     . 335,340,355,395,410,415,430,450/
      DATA ((BST(I,J),J=1,26),I=1,16)/
     . 184,181,179,176,173,170,167,164,151,158,155,152,149,146,143,
     . 140,137,134,132,129,126,123,120,118,115,112,
     . 199,196,193,189,186,183,179,176,173,169,166,163,159,156,152,
     . 149,146,142,139,136,133,130,127,124,121,119,
     . 206,203,199,196,192,189,165,182,178,175,171,168,164,160,157,
     . 153,150,146,143,139,136,133,130,127,123,120,
     . 213,210,206,202,199,195,191,188,184,180,176,172,169,165,161,
     . 157,154,150,146,143,139,136,133,129,126,123,
     . 220,217,213,209,205,201,197,193,189,185,181,177,173,169,165,
     . 161,157,154,150,146,142,139,135,132,129,125,
     . 241,237,232,228,223,219,214,210,205,200,195,191,186,181,177,
     . 172,168,163,159,155,151,147,143,139,135,132,
     . 252,247,242,237,232,227,222,217,212,207,202,197,192,[illegible]
     . 177,173,168,163,159,155,150,146,142,138,134,
     . 255,250,245,240,235,230,225,220,215,210,204,199,19[illegible]
     . 173,174,169,165,160,156,152,147,143,139,135,
     . 262,257,252,246,241,236,230,225,220,214,209,203,198,193,187,
     . 182,177,172,168,163,159,154,149,145,141,137,
     . 265,260,255,249,244,238,233,227,222,216,211,205,200,194,189,
     . 184,179,174,169,164,159,155,150,146,142,138,
     . 275,270,264,258,252,247,241,235,229,223,217,211,205,200,194,
     . 189,183,178,173,168,163,158,153,149,145,140,
     . 301,294,288,281,274,267,260,253,246,239,232,226,219,212,206,
     . 200,193,187,182,176,171,165,160,155,151,146,
     . 310,303,296,289,282,274,267,260,252,245,238,231,223,217,210,
     . 203,197,191,185,179,173,168,163,158,153,148,
     . 314,306,299,292,284,277,269,262,254,247,239,232,225,218,211,
     . 205,198,192,186,180,174,169,163,158,154,149,
     . 323,315,308,300,292,244,276,268,260,252,244,237,229,222,215,
     . 203,201,195,189,181,177,177,165,160,155,151,
     . 335,327,319,310,302,293,285,276,268,259,251,243,235,227,220,
     . 213,205,199,192,186,180,174,168,163,158,153/
      DATA (ECCST(I),I=1,110)/
     . .3301,.3274,.3247,.3217,[illegible],[illegible],.3129,.3097,.3064,.3030,
     . [illegible],.4959,[illegible],[illegible],[illegible],[illegible],.4759,.4711,.4670,.4621,
     . [illegible],.4525,.8474,.4421,[illegible],[illegible],[illegible],[illegible],[illegible],[illegible],
     . .9007,.7941,.7875,.7807,.7737,.7667,.7595,.7522,.7449,.7374,
     . .7298,.7222,.7146,.7063,.6991,.6913,.6834,.6756,.6678,.6600,
     . .6521,.6444,.6366,.6289,.6212,.6136,.6060,.5985,.5910,.5837,
     . [illegible],[illegible],[illegible],[illegible],[illegible],[illegible],[illegible],[illegible],[illegible],[illegible],
     . [illegible],[illegible],[illegible],[illegible],[illegible],[illegible],.479,[illegible],[illegible],[illegible],
```

165

```
     . .4431,.4426,.4372,.4319,.4266,.4215,.4164,.4113,.4063,.4017,
     . .3963,.3922,.3876,.3831,.3786,.3742,.3698,.3657,.3615,.3571,
     . .3533,.3493,.3454,.3415,.3377,.3339,.3302,.3266,.3230,.3195/
       DATA (ECCSL(I),I=1,110)/
     . 0.60,0.61,0.62,0.63,0.64,0.65,0.66,0.67,0.68,0.69,
     . 0.70,0.71,0.72,0.73,0.74,0.75,0.76,0.77,0.78,0.79,
     . 0.80,0.81,0.82,0.83,0.84,0.85,0.86,0.87,0.88,0.89,
     . 0.90,0.91,0.92,0.93,0.94,0.95,0.96,0.97,0.98,0.99,
     . 1.00,1.01,1.02,1.03,1.04,1.05,1.06,1.07,1.08,1.09,
     . 1.10,1.11,1.12,1.13,1.14,1.15,1.16,1.17,1.18,1.19,
     . 1.20,1.21,1.22,1.23,1.24,1.25,1.26,1.27,1.28,1.29,
     . 1.30,1.31,1.32,1.33,1.34,1.35,1.36,1.37,1.38,1.39,
     . 1.40,1.41,1.42,1.43,1.44,1.45,1.46,1.47,1.48,1.49,
     . 1.50,1.51,1.52,1.53,1.54,1.55,1.56,1.57,1.58,1.59,
     . 1.60,1.61,1.62,1.63,1.64,1.65,1.66,1.67,1.68,1.69/
CC     RETURN
       END
**
**
**
       SUBROUTINE BSV(ALAM,PY,PC,AREA,P)
**     ROUTINE TO CALCULATE Pc AS PER BS : 5950, TABLE 27[redacted]
**     block data supplies Perry-Robertson formula values[redacted]

       DIMENSION BST(16,100),BSLAM(100),BSPY(16),ECCSL(300),ECCST(300)
       COMMON/CODETAB/BST,BSLAM,BSPY,ECCSL,ECCST,NXBS,NYBS,NECCS
       IX=NXBS
       IY=NYBS
       IY1=0
       IX1=0
       IF(ALAM.LT.BSLAM(1))THEN
       IY1=1
       ELSE IF(ALAM.LE.BSLAM(IY)) THEN
       DO 100 I=1,IY
       IF(IY1.EQ.0.AND.ALAM.LE.BSLAM(I))THEN
       IY1=I
       ENDIF
 100   CONTINUE
       ELSE
       IY1=IY
       ENDIF
       IF(PY.LE.BSPY(1))THEN
       IX1=1
       ELSE IF(PY.LE.BSPY(IX))THEN
       DO 200 I=1,IX
       IF(PY.LE.BSPY(I).AND.IX1.EQ.0)THEN
       IX1=I-1
       ENDIF
 200   CONTINUE
       ELSE
```

```
      IX1=IX
      ENDIF
      IF(IX1.NE.IX) THEN
      PC=BST(IX1+1,IY1)
      ELSE
      PC=BST(IX1,IY1)
      ENDIF
      P=PC*AREA
      RETURN
      END
**
**
**
      SUBROUTINE ECCSV(ALAM,PY,PC,AREA,P)
**    routine to compute P as per ECCS recommendations
**    Block data supplies table values from the non-dimensional column
**      buckling curve from ECCS Recommendations
      DIMENSION BST(16,100),BSLAM(100),BSPY(16),ECCSL(300),ECCST(300)
      COMMON/CODETAB/BST,BSLAM,BSPY,ECCSL,ECCST,NXBS,NYBS,NECCS
      IN1=0
      IF(ALAM.LT.ECCSL(1))THEN
      IN1=1
      ELSE IF(ALAM.LE.ECCSL(NECCS))THEN
      DO 100 I=1,NECCS
      IF(ALAM.LE.ECCSL(I).AND.IN1.EQ.0) THEN
      IN1=I
      ENDIF
  100 CONTINUE
      ELSE
      IN1=NECCS
      ENDIF
      FACT=ECCST(IN1)
      PC=PY*FACT
      P=AREA*PC
      RETURN
      END
```

Appendix D

TYPICAL FINITE ELEMENT MODEL FOR SCHIFFLERIZED ANGLES USING ABAQUS

A B A Q U S

THIS PROGRAM HAS BEEN DEVELOPED BY

HIBBITT, KARLSSON AND SORENSEN, INC.
100 MEDWAY STREET
PROVIDENCE, R.I. 02906

THIS IS A PROPRIETARY PROGRAM AND IS MADE AVAILABLE FOR INTERNAL USE AT UNIVERSITY OF WINDSOR, UNDER THE TERMS OF THE ACADEMIC LICENSE AGREEMENT WITH H.K.S. ALL USAGE MUST BE UNDER THE DIRECT SUPERVISION AND CONTROL OF THE DESIGNATED USER. THE DESIGNATED USER IS DR. GEORGE ABDEL-SAYED. ANY NON-ACADEMIC USAGE OF THE PROGRAM REQUIRES PAYMENT OF A MONTHLY CHARGE. ASSISTANCE AND OTHER INFORMATION MAY BE OBTAINED FROM THE DESIGNATED USER.

FOR ASSISTANCE OR ANY OTHER INFORMATION CALL
401-861-0920

N O T I C E

THIS IS ABAQUS VERSION 4-7.

SOME INPUT DATA OPTIONS AND USER SUBROUTINE INTERFACES ARE INCOMPATIBLE WITH VERSION 4-5.

PLEASE MAKE SURE YOU ARE USING VERSION 4-6 OR 4-7 MANUALS.

```
  ABAQUS PRODUCTION VERSION 4-7-22                    DATE  5MAY 90      TIME 17:26:15        PAGE    2
 FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

*PREPRINT,ECHO=YES,MODEL=YES,HISTORY=YES
```

A B A Q U S   I N P U T   E C H O

```
    5    10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
--------------------------------------------------------------------------------
*HEADING
60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
**60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-FLEXURAL  BUCKLING
**60 DEG. 4x4x1/4"  SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
**60 DEG. 4x4x1/4"  SHELL ELEMENTS-END PLATES LOAD-FLEXURAL BUCKLING
**60 DEG. 3.5x3.5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
**60 DEG. 3.5x3.5x5/16" SHELL ELEMENTS-END PLATES LOAD-FLEXURAL BUCKLING
**60 DEG. 3x3x3/8"  SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
**60 DEG. 3x3x3/8"  SHELL ELEMENTS-END PLATES LOAD-FLEXURAL BUCKLING
**60 DEG. 3x3x1/4"  SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
**60 DEG. 3x3x1/4"  SHELL ELEMENTS-END PLATES LOAD-FLEXURAL BUCKLING
SCHIFFLERISED 60-DEG. HOT ROLLED ANGLE - 65.125" long
 modelled  with  8-node  rectangular shell elements (curves at root and
 toe neglected). Constant  element  thickness * leg  thickness  of  the
 element. Length of unbent original 90-deg. angle taken as per industry
 standards.
Residual stress   patterns are taken from ECCS recommendations. Through
 the thickness  variation  is  estimated  as  poissons  ratio times the
 superimposition  of  full  section  plastic  stress  and  full section
 elastic  unloading  stress  around  the  bend line of schifflerisation.
 The residual  stresses  are  input  as  initial  stresses through user
 defined subroutine SIGINI. All  residual stress is  given at the Gauss
 integration points.
Boundary conditins : the top and bottom centriodal points are prevented
 from lateral translation and  twisting  rotation along the member axis.
Loading : the member is loaded concentrically at section centriod point
 located an end plate.
Initial out of straightness : the member  buckling  is achieved through
 usage of a nonlinear geometry option. For this to function, an initial
 crookedness in the geometry is introduced through triggar loads
 designed to create the desired buckling mode.
**
*DATACHECK
**
*PREPRINT,ECHO=YES,MODEL=YES,HISTORY=YES
*****************************************************************
*NODE
***5x5x5/16"angle section
      1,      0.000000000,    101.868346000,    -65.112274200
      9,      0.000000000,     14.902277000,    -14.902277000
--------------------------------------------------------------------------------
    5    10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
```

```
ABAQUS PRODUCTION VERSION 4-7-22                              DATE  5MAY 90      TIME 17:26:15        PAGE    4
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

    5   10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
------------------------------------------------------------------------------------
     17,     0.000000000,     0.000000000,     0.000000000
    177,     0.000000000,    14.902277000,    14.902277000
    337,     0.000000000,   101.868546000,    65.112274200
    169,     0.000000000,    49.550109900,     0.000000000
    161,     0.000000000,   126.643616000,   -40.337219200
    329,     0.000000000,   126.643616000,    40.337219200
    321,     0.000000000,   166.980835000,     0.000000000
***4x4x1/4"angle section
**    1,     0.000000000,    81.287338300,   -53.172927900
**    9,     0.000000000,    14.767924300,   -14.767924300
**   17,     0.000000000,     0.000000000,     0.000000000
**  177,     0.000000000,    14.767924300,    14.767924300
**  337,     0.000000000,    81.287338300,    53.172927900
**  169,     0.000000000,    39.338897700,     0.000000000
**  161,     0.000000000,   100.956787000,   -33.503463700
**  329,     0.000000000,   100.956787000,    33.503463700
**  321,     0.000000000,   134.450266000,     0.000000000
***3.5x3.5x5/16"angle section
**    1,     0.000000000,    71.236679100,   -47.411712600
**    9,     0.000000000,    14.866207100,   -14.866207100
**   17,     0.000000000,     0.000000000,     0.000000000
**  177,     0.000000000,    14.866207100,    14.866207100
**  337,     0.000000000,    71.236679100,    47.411712600
**  169,     0.000000000,    34.355606100,     0.000000000
**  161,     0.000000000,    88.414474500,   -30.233902000
**  329,     0.000000000,    88.414474500,    30.233902000
**  321,     0.000000000,   118.648392000,     0.000000000
***3x3x3/8"angle section
**    1,     0.000000000,    58.472198500,   -40.097717300
**    9,     0.000000000,    14.997732200,   -14.997732200
**   17,     0.000000000,     0.000000000,     0.000000000
**  177,     0.000000000,    14.997732200,    14.997732200
**  337,     0.000000000,    58.472198500,    40.097717300
**  169,     0.000000000,    28.051300000,     0.000000000
**  161,     0.000000000,    72.497863800,   -26.072082500
**  329,     0.000000000,    72.497863800,    26.072082500
**  321,     0.000000000,    98.569946300,     0.000000000
***3x3x1/4"angle section
**    1,     0.000000000,    60.667251600,   -41.267913800
**    9,     0.000000000,    14.767924300,   -14.767924300
**   17,     0.000000000,     0.000000000,     0.000000000
**  177,     0.000000000,    14.767924300,    14.767924300
**  337,     0.000000000,    60.667251600,    41.267913800
**  169,     0.000000000,    29.143203700,     0.000000000
------------------------------------------------------------------------------------
    5   10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
```

```
ABAQUS PRODUCTION VERSION 4-7-22                          DATE  5MAY 90     TIME 17:26:15       PAGE    5
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

          5    10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
     --------------------------------------------------------------------------------
     ** 161,      0.000000000,     75.238861100,    -26.696319600
     ** 329,      0.000000000,     75.238861100,     26.696319600
     ** 321,      0.000000000,    101.935195000,      0.000000000
     ****************************************************************
     *NGEN,NSET=D1
     1,9,2
     9,17,2
     *NGEN,NSET=D2
     161,169,2
     169,177,2
     *NGEN,NSET=D3
     321,329,2
     329,337,2
     *NFILL,NSET=D4
     D1,D2,4,40
     *NFILL,NSET=D5
     D2,D3,4,40
     *NSET,NSET=BOT
     D4,D5
     *NCOPY,CHANGE NUMBER=10000,OLDSET=BOT,SHIFT,NEW SET=TOP
     **65.125 " EFFECTIVE LENGTH
     1654.175
     0.0
     *NSET,NSET=END1,GENERATE
     1,17,2
     17,337,40
     *NSET,NSET=END2,GENERATE
     10001,10017,2
     10017,10337,40
     *NFILL,NSET=JANGLE
     END1,END2,10,1000
     ****************************************************************
     *ELEMENT,TYPE=S8R
     **ELEMENT DATA
     101,1,2001,2005,5,1001,2003,1005,3
     105,17,2017,2097,97,1017,2057,1097,57
     *ELGEN,ELSET=ANGLE
     101,5,2000,100,4,4,1
     105,5,2000,100,4,80,1
     *ELSET,ELSET=E1,GENERATE
     1,501,100
     2,502,100
     *ELSET,ELSET=E2,GENERATE
     3,503,100
     --------------------------------------------------------------------------------
          5    10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
```

```
ABAQUS PRODUCTION VERSION 4-7-22                          DATE  5MAY 90      TIME 17:26:15          PAGE    6
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

         5   10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
   --------------------------------------------------------------------------------
   4,504,100
   *ELSET,ELSET=E3,GENERATE
   5,505,100
   6,506,100
   *ELSET,ELSET=E4,GENERATE
   7,507,100
   8,508,100
   *ELSET,ELSET=FIGURE,GENERATE
   1,8,1
   *ELEMENT,TYPE=S8R,ELSET=PLATE
   1,1,81,85,5,41,83,45,3
   *ELGEN,ELSET=PLATE
   1,4,4,1,4,80,10
   *ELCOPY,ELEMENT SHIFT=50,OLD SET=PLATE,NEW SET=PLATE,SHIFT NODES=10000
   ************************************************************************
   *MATERIAL,NAME=M1
   *ELASTIC
   **IMPERIAL UNITS 29.0E6 ksi
   200.0E3,0.3000
   *PLASTIC
   **IMPERIAL UNITS 44.E3,0.0
   **5-5-5/16 SECTION 2% YIELD STRESS (MPA)
   332.0
   **4-4-1/4 SECTION 2% YIELD STRESS  (MPA)
   **356.0
   **3 1/2 - 3 1/2 - 5/16 SECTION 2% YIELD STRESS (MPA)
   **369.0
   **3-3-3/8 SECTION 2% YIELD STRESS (475.0MPA)
   **375.0
   **3-3-1/4 SECTION 2% YIELD STRESS
   **363.0
   *MATERIAL,NAME=M2
   *ELASTIC
   **MATERIAL FOR END PLATES ONLY ELASTIC
   200.0E3,0.3000
   ************************************************************************
   *BOUNDARY
   169,1,4
   10169,2,4
   ************************************************************************
   *SHELL SECTION,ELSET=ANGLE,MATERIAL=M1
   **5-5-5/16 SECTION THICKNESS (mm)
   7.8333333,13
   **4-4-1/4 SECTION
   --------------------------------------------------------------------------------
         5   10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
```

```
ABAQUS PRODUCTION VERSION 4-7-22                              DATE  5MAY 90      TIME 17:26:15         PAGE     7
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

         5    10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
--------------------------------------------------------------------------------
**6.252,13
**3 1/2 - 3 1/2 - 5/16 SECTION
**8.0912,13
**3-3-3/8 SECTION
**9.82,13
**3-3-1/4 SECTION
**6.4092,13
*SHELL SECTION,ELSET=PLATE,MATERIAL=M2
150.0
*****************************************************************
*INITIAL CONDITIONS, TYPE=STRESS,USER
*USER SUBROUTINES
       SUBROUTINE SIGINI(SIGMA,COORDS,NTENS,NCRDS,NOEL)
CC SUBROUTINE TO DEFINE AN INITIAL STRESS FIELD
CC 60 DEGREE SCHFFLERISED ANGLE
       DIMENSION SIGMA(NTENS),COORDS(NCRDS)
CC TRIAL STRESS FIELD FOR 1/4 YIELD STRESS TRIANGULAR VARIATION
CC THROUGH THE THICKNESS VARIATION INCLUDED WITH POISSONS RATIO OF 0.3
CC C=UNBENT PORTON - THICKNESS /2 ; T=THICKNESS
CC W=TOTAL LEG WIDTH OUTER DIMENSION ; A=UNBENT PORTION
**60 DEG. 5x5x5/16" SPECIMEN #1 SHELL ELEMENTS-END PLATES LOAD
       DATA W,A,T,YIELD/125.4125,25.0,7.8483,332.0
**60 DEG. 4x4x1/4" SPECIMEN #1 SHELL ELEMENTS-END PLATES LOAD
**     DATA W,A,T,YIELD/100.81,24.0,6.23,356.0
**60 DEG. 3.5x3.5x5/16" SPECIMEN #1 SHELL ELEMENTS-END PLATES LOAD
**     DATA W,A,T,YIELD/90.091,25.0,7.952,369.0
**60 DEG. 3x3x3/8" SPECIMEN #1 SHELL ELEMENTS-END PLATES LOAD
**     DATA W,A,T,YIELD/76.2,26.0,9.577,375.0
**60 DEG. 3x3x1/4" SPECIMEN #1 SHELL ELEMENTS-END PLATES LOAD
**     DATA W,A,T,YIELD/77.0,24.0,6.229,363.0
       YIELD=375.E3
       PI=3.141592654
       D=W-T/2.0
       B=W-A
       C=A-T/2.0
       IF(NOEL.LT.100) AK=0.0
       IF(NOEL.LT.100) RETURN
       AK=AK+1.
       IF(AK.GT.13.) AK=AK-13.
       X=SQRT(COORDS(3)**2+COORDS(5)**2)
       IF(X.LE.C)THEN
       X=X/(B+C)
       ELSE
       XX=ABS(COORDS(3))-C/SQRT(2.0)
--------------------------------------------------------------------------------
         5    10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
```

```
    5    10    15    20    25    30    35    40    45    50    55    60    65    70    75    80
--------------------------------------------------------------------------------
      YY=ABS(COORDS(5))-C/SQRT(2.0)
      X=(C+SQRT(XX*XX+YY*YY))/(B+C)
      ENDIF
      IF(X.LE.0.5) THEN
      SIGMA(1)=0.25*YIELD*(X*4.0-1.0)
      ELSE
      SIGMA(1)=0.25*YIELD*(3.0-4.0*X)
      ENDIF
      IF(X.LT.(C+B/2)/(C+B).AND.X.GT.(C/2)/(C+B)) THEN
          IF(AK.LT.7) THEN
          SIGMA(1)=0.3*(0.5*YIELD-1.50*YIELD*(AK-1)/5)+SIGMA(1)
          ELSE IF(AK.GT.7) THEN
          SIGMA(1)=SIGMA(1)+0.3*(1.5*YIELD*(13-AK)/5-0.5*YIELD)
          ENDIF
      ENDIF
CC    PRINT 200,NOEL,AK,(SIGMA(I),I=1,NTENS)
  200 FORMAT(/5X,
     .'ELEMENT NUMBER: ',I5,'POINT ',I2,/' STRESSES : ',7E13.6)
CC    PRINT 300,(COORDS(I),I=1,NCRDS)
  300 FORMAT(5X,'COORDINATES : ',6E15.8)
CC    PRINT 800,(SIGMA(I),I=1,NTENS)
  800 FORMAT(/5X,'INITIAL STRESS : ',/5X,7E13.6)
CC    PRINT 900
  900 FORMAT(1X,79('*'))
      RETURN
      END
**********************************************************************
*PLOT
60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
**60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-FLEXURAL  BUCKLING
**60 DEG. 4x4x1/4"  SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
**60 DEG. 4x4x1/4"  SHELL ELEMENTS-END PLATES LOAD-FLEXURAL BUCKLING
**60 DEG. 3.5x3.5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
**60 DEG. 3.5x3.5x5/16" SHELL ELEMENTS-END PLATES LOAD-FLEXURAL BUCKLING
**60 DEG. 3x3x3/8"  SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
**60 DEG. 3x3x3/8"  SHELL ELEMENTS-END PLATES LOAD-FLEXURAL BUCKLING
**60 DEG. 3x3x1/4"  SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
**60 DEG. 3x3x1/4"  SHELL ELEMENTS-END PLATES LOAD-FLEXURAL BUCKLING
0
0.20, , , , , ,0.05
*NOERASE
*DETAIL,ELSET=ANGLE,SECTION SCALING=20.
*VIEW POINT,DEFINITION=MODEL AXIS ROTATION
0.0,90.0
--------------------------------------------------------------------------------
    5    10    15    20    25    30    35    40    45    50    55    60    65    70    75    80
```

```
ABAQUS PRODUCTION VERSION 4-7-22                       DATE  5MAY 90      TIME 17:26:15          PAGE     9
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

                  5    10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
              ----------------------------------------------------------------------------------
              *DRAW
              *DETAIL,ELSET=PLATE,SECTION SCALING=20.
              *SHRINK,FACTOR=0.1
              *VIEW POINT,DEFINITION=MODEL AXIS ROTATION
CARD  265     0.0,90.0
              *DRAW
              *ERASE
              *VIEW POINT
              0.5,1.0,0.5
CARD  270     *SHRINK,FACTOR=0.2
              *DETAIL,ELSET=ANGLE
              *DRAW
              *DETAIL,ELSET=FIGURE
              *DRAW
CARD  275     *DETAIL,NSET=JANGLE
              *PLOT MODE,DOTSIZE=0.002
              *DRAW,NODENUM
              *SHRINK
              **********************************************************************
CARD  280     *STEP,NLGEOM
              ** TRIGGER LOADS
              *STATIC,PTOL=200.,MTOL=200.
              *NODE PRINT,FREQ=1
              **U
CARD  285     RF
              *ELPRINT,FREQ=0
              *CLOAD
              **FOR FLEXURAL BUCKLING - APPLY SMALL MOMENTS AT ENDS
              169,6,-500.0
CARD  290     10169,6,500.0
              **FOR TORSIONAL BUCKLING - APPLY SMALL MOMENTS IN MAJOR AXIS PLANE
              169,5,-500.0
              10169,5,500.0
              *DETAIL,ELSET=ANGLE
CARD  295     *VIEW POINT,DEFINITION=MODEL AXIS ROTATION
              45.0
              *DISPLACED
              U
              *END STEP
CARD  300     *********************************  ********************************
              *STEP,NLGEOM,INC=500
              *STATIC,PTOL=500.0,MTOL=500.0
              0.1,1.0,0.001,0.1
              *ELPRINT,FREQ=2
              ----------------------------------------------------------------------------------
                  5    10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
```

```
ABAQUS PRODUCTION VERSION 4-7-22                        DATE  5MAY 90      TIME 17:26:15        PAGE   10
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

                   5    10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
              --------------------------------------------------------------------------------
CARD  305     **S
              **E
              **SP
              **CE,CEEQ
              *NODE PRINT,FREQ=1
CARD  310     **U
              *NODE PRINT,FREQ=1
              RF
              *ELFILE,FREQ=0
              **SP
CARD  315     **CE
              *NODE FILE,FREQ=0
              **U
              *PRINT,RESIDUAL=NO
              *CLOAD
CARD  320     10169,1,-900.0E3
              *PLOT,FREQ=3
              *PLOTMODE,DOTSIZE=0.005
              *SHRINK,FACTOR=0.0
              *ZOOM,FACTOR=1.5
CARD  325     *DETAIL,ELSET=E1
              *CENTER
              825.0,0.0,0.0
              *VIEW POINT,DEFINITION=MODEL AXIS ROTATION
              30.0
CARD  330     *NOERASE
              *CONTOUR
              S11,4
              *DETAIL,ELSET=E2
              *CENTER
CARD  335     825.0,0.0,0.0
              *VIEW POINT,DEFINITION=MODEL AXIS ROTATION
              45.0
              *CONTOUR
              S11,4
CARD  340     *DETAIL,ELSET=E3
              *CENTER
              825.,0.0,0.0
              *VIEW POINT,DEFINITION=MODEL AXIS ROTATION
              135.0
CARD  345     *CONTOUR
              S11,4
              *DETAIL,ELSET=E4
              *CENTER
              --------------------------------------------------------------------------------
                   5    10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
```

```
  ABAQUS PRODUCTION VERSION 4-7-22                           DATE  5MAY 90      TIME 17:26:15        PAGE   11
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

                    5   10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
                 ----------------------------------------------------------------------------------
                 825.,0.0,0.0
  CARD  350      *VIEW POINT,DEFINITION=MODEL AXIS ROTATION
                 150.0
                 *CONTOUR
                 S11,4
                 *ERASE
  CARD  355      *DETAIL,ELSET=ANGLE
                 *ZOOM,FACTOR=1.0
                 *VIEWPOINT,DEFINITION=MODEL AXIS ROTATION
                 0.0
                 *DISPLACED
  CARD  360      U
                 *DETAIL,ELSET=ANGLE
                 *ZOOM,FACTOR=1.0
                 *VIEWPOINT,DEFINITION=MODEL AXIS ROTATION
                 90.0
  CARD  365      *DISPLACED
                 U
                 *DETAIL,ELSET=ANGLE
                 *ZOOM,FACTOR=1.0
                 *VIEWPOINT,DEFINITION=MODEL AXIS ROTATION
  CARD  370      0.0,90.0
                 *DISPLACED
                 U
                 *END STEP
                 ----------------------------------------------------------------------------------
                    5   10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
                 ----------------------------------------------------------------------------------
```

```
ABAQUS PRODUCTION VERSION 4-7-22                          DATE  5MAY 90      TIME 17:26:15        PAGE   12
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.


OPTIONS BEING PROCESSED
**************************

*HEADING
     60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
     SCHIFFLERISED 60-DEG. HOT ROLLED ANGLE - 65.125" long
      modelled  with  8-node  rectangular shell elements (curves at root and
      toe neglected). Constant  element  thickness = leg  thickness  of  the
      element. Length of unbent original 90-deg. angle taken as per industry
      standards.
     Residual stress   patterns are taken from ECCS recommendations. Through
      the thickness  variation  is  estimated  as  poissons  ratio times the
      superimposition  of  full  section  plastic  stress  and  full section
      elastic  unloadimg  stress  around  the  bend line of schifflerisation.
      The residual  stresses  are  input  as  initial  stresses through user
      defined subroutine SIGINI. All  residual stress is  given at the Gauss
      integration points.
     Borndary conditins : the top and bottom centriodal points are prevented
      from lateral translation and  twisting  rotation along the member axis.
     Loading : the member is loaded concentrically at section centriod point
      located an end plate.
     Initial out of straightness : the member  buckling  is achieved through
      usage of a nonlinear geometry option. For this to function, an initial
      crookedness in the geometry is introduced through triggar loads
      designed to create the desired buckling mode.
*NODE
*NGEN,NSET=D1
*NGEN,NSET=D2
*NGEN,NSET=D3
*NFILL,NSET=D4

  THE FOLLOWING NODES WILL BE USED IN THE NFILL GENERATION


     BOUND  1          1     3     5     7     9    11    13    15    17

     BOUND  2        161   163   165   167   169   171   173   175   177
*NFILL,NSET=D5

  THE FOLLOWING NODES WILL BE USED IN THE NFILL GENERATION


     BOUND  1        161   163   165   167   169   171   173   175   177

     BOUND  2        321   323   325   327   329   331   333   335   337
```

```
-----

  ABAQUS PRODUCTION VERSION 4-7-22                          DATE  5MAY 90      TIME 17:26:15        PAGE   13
 FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

  60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
*NSET,NSET=BOT
*NCOPY,CHANGE NUMBER=10000,OLDSET=BOT,SHIFT,NEW SET=TOP
*NSET,NSET=END1,GENERATE
*NSET,NSET=END2,GENERATE
*NFILL,NSET=JANGLE

  THE FOLLOWING NODES WILL BE USED IN THE NFILL GENERATION

     BOUND  1          1     3     5     7     9    11    13    15    17    57    97   137   177   217   257
                     297   337

     BOUND  2      10001 10003 10005 10007 10009 10011 10013 10015 10017 10057 10097 10137 10177 10217 10257
                   10297 10337
*ELEMENT,TYPE=S8R
*ELGEN,ELSET=ANGLE
*ELSET,ELSET=E1,GENERATE
*ELSET,ELSET=E2,GENERATE
*ELSET,ELSET=E3,GENERATE
*ELSET,ELSET=E4,GENERATE
*ELSET,ELSET=FIGURE,GENERATE
*ELEMENT,TYPE=S8R,ELSET=PLATE
*ELGEN,ELSET=PLATE
*ELCOPY,ELEMENT SHIFT=50,OLD SET=PLATE,NEW SET=PLATE,SHIFT NODES=10000
*MATERIAL,NAME=M1
*ELASTIC
*PLASTIC
*MATERIAL,NAME=M2
*ELASTIC
*SHELL SECTION,ELSET=ANGLE,MATERIAL=M1
*SHELL SECTION,ELSET=PLATE,MATERIAL=M2
*INITIAL CONDITIONS, TYPE=STRESS,USER
*INITIAL CONDITIONS, TYPE=STRESS,USER
*INITIAL CONDITIONS, TYPE=STRESS,USER
*STEP,NLGEOM
*STATIC,PTOL=200.,MTOL=200.
*ELPRINT,FREQ=0
*DETAIL,ELSET=ANGLE
*VIEW POINT,DEFINITION=MODEL AXIS ROTATION
*DISPLACED
*END STEP
*STEP,NLGEOM,INC=500
*STATIC,PTOL=500.0,MTOL=500.0
*ELPRINT,FREQ=2
*ELFILE,FREQ=0
*PRINT,RESIDUAL=NO
*PLOT,FREQ=3
*PLOTMODE,DOTSIZE=0.005
```

```
  60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
*SHRINK,FACTOR=0.0
*ZOOM,FACTOR=1.5
*DETAIL,ELSET=E1
*CENTER
*VIEW POINT,DEFINITION=MODEL AXIS ROTATION
*NOERASE
*CONTOUR
*DETAIL,ELSET=E2
*CENTER
*VIEW POINT,DEFINITION=MODEL AXIS ROTATION
*CONTOUR
*DETAIL,ELSET=E3
*CENTER
*VIEW POINT,DEFINI     =MODEL AXIS ROTATION
*CONTOUR
*DETAIL,ELSET=E4
*CENTER
*VIEW POINT,DEFINITION=MODEL AXIS ROTATION
*CONTOUR
*ERASE
*DETAIL,ELSET=ANGLE
*ZOOM,FACTOR=1.0
*VIEWPOINT,DEFINITION=MODEL AXIS ROTATION
*DISPLACED
*DETAIL,ELSET=ANGLE
*ZOOM,FACTOR=1.0
*VIEWPOINT,DEFINITION=MODEL AXIS ROTATION
*DISPLACED
*DETAIL,ELSET=ANGLE
*ZOOM,FACTOR=1.0
*VIEWPOINT,DEFINITION=MODEL AXIS ROTATION
*DISPLACED
*END STEP
*BOUNDARY
*STEP,NLGEOM
*STATIC,PTOL=200.,MTOL=200.
*NODE PRINT,FREQ=1
*CLOAD
*STEP,NLGEOM,INC=500
*STATIC,PTOL=500.0,MTOL=500.0
*NODE PRINT,FREQ=1
*NODE PRINT,FREQ=1
*NODE FILE,FREQ=0
*CLOAD
```

60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING

E L E M E N T D E F I N I T I O N S

NUMBER	TYPE	PROPERTY REFERENCE	NODES FORMING ELEMENT							
1	S8R	2	1	81	85	5	41	83	45	3
2	S8R	2	5	85	89	9	45	87	49	7
3	S8R	2	9	89	93	13	49	91	53	11
4	S8R	2	13	93	97	17	53	95	57	15
11	S8R	2	81	161	165	85	121	163	125	83
12	S8R	2	85	165	169	89	125	167	129	87
13	S8R	2	89	169	173	93	129	171	133	91
14	S8R	2	93	173	177	97	133	175	137	95
21	S8R	2	161	241	245	165	201	243	205	163
22	S8R	2	165	245	249	169	205	247	209	167
23	S8R	2	169	249	253	173	209	251	213	171
24	S8R	2	173	253	257	177	213	255	217	175
31	S8R	2	241	321	325	245	281	323	285	243
32	S8R	2	245	325	329	249	285	327	289	247
33	S8R	2	249	329	333	253	289	331	293	251
34	S8R	2	253	333	337	257	293	335	297	255
51	S8R	2	10001	10081	10085	10005	10041	10083	10045	10003
52	S8R	2	10005	10085	10089	10009	10045	10087	10049	10007
53	S8R	2	10009	10089	10093	10013	10049	10091	10053	10011
54	S8R	2	10013	10093	10097	10017	10053	10095	10057	10015
61	S8R	2	10081	10161	10165	10085	10121	10163	10125	10083
62	S8R	2	10085	10165	10169	10089	10125	10167	10129	10087
63	S8R	2	10089	10169	10173	10093	10129	10171	10133	10091
64	S8R	2	10093	10173	10177	10097	10133	10175	10137	10095
71	S8R	2	10161	10241	10245	10165	10201	10243	10205	10163
72	S8R	2	10165	10245	10249	10169	10205	10247	10209	10167
73	S8R	2	10169	10249	10253	10173	10209	10251	10213	10171
74	S8R	2	10173	10253	10257	10177	10213	10255	10217	10175
81	S8R	2	10241	10321	10325	10245	10281	10323	10285	10243
82	S8R	2	10245	10325	10329	10249	10285	10327	10289	10247
83	S8R	2	10249	10329	10333	10253	10289	10331	10293	10251
84	S8R	2	10253	10333	10337	10257	10293	10335	10297	10255
101	S8R	1	1	2001	2005	5	1001	2003	1005	3
102	S8R	1	5	2005	2009	9	1005	2007	1009	7
103	S8R	1	9	2009	2013	13	1009	2011	1013	11
104	S8R	1	13	2013	2017	17	1013	2015	1017	15
105	S8R	1	17	2017	2097	97	1017	2057	1097	57
106	S8R	1	97	2097	2177	177	1097	2137	1177	137
107	S8R	1	177	2177	2257	257	1177	2217	1257	217
103	S8R	1	257	2257	2337	337	1257	2297	1337	297
201	S8R	1	2001	4001	4005	2005	3001	4003	3005	2003

ABAQUS PRODUCTION VERSION 4-7-22 DATE 5MAY 90 TIME 17:26:15 PAGE 16
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING

202	S8R	1	2005	4005	4009	2009	3005	4007	3009	2007
203	S8R	1	2009	4009	4013	2013	3009	4011	3013	2011
204	S8R	1	2013	4013	4017	2017	3013	4015	3017	2015
205	S8R	1	2017	4017	4097	2097	3017	4057	3097	2057
206	S8R	1	2097	4097	4177	2177	3097	4137	3177	2137
207	S8R	1	2177	4177	4257	2257	3177	4217	3257	2217
208	S8R	1	2257	4257	4337	2337	3257	4297	3337	2297
301	S8R	1	4001	6001	6005	4005	5001	6003	5005	4003
302	S8R	1	4005	6005	6009	4009	5005	6007	5009	4007
303	S8R	1	4009	6009	6013	4013	5009	6011	5013	4011
304	S8R	1	4013	6013	6017	4017	5013	6015	5017	4015
305	S8R	1	4017	6017	6097	4097	5017	6057	5097	4057
306	S8R	1	4097	6097	6177	4177	5097	6137	5177	4137
307	S8R	1	4177	6177	6257	4257	5177	6217	5257	4217
308	S8R	1	4257	6257	6337	4337	5257	6297	5337	4297
401	S8R	1	6001	8001	8005	6005	7001	8003	7005	6003
402	S8R	1	6005	8005	8009	6009	7005	8007	7009	6007
403	S8R	1	6009	8009	8013	6013	7009	8011	7013	6011
404	S8R	1	6013	8013	8017	6017	7013	8015	7017	6015
405	S8R	1	6017	8017	8097	6097	7017	8057	7097	6057
406	S8R	1	6097	8097	8177	6177	7097	8137	7177	6137
407	S8R	1	6177	8177	8257	6257	7177	8217	7257	6217
408	S8R	1	6257	8257	8337	6337	7257	8297	7337	6297
501	S8R	1	8001	10001	10005	8005	9001	10003	9005	8003
502	S8R	1	8005	10005	10009	8009	9005	10007	9009	8007
503	S8R	1	8009	10009	10013	8013	9009	10011	9013	8011
504	S8R	1	8013	10013	10017	8017	9013	10015	9017	8015
505	S8R	1	8017	10017	10097	8097	9017	10057	9097	8057
506	S8R	1	8097	10097	10177	8177	9097	10137	9177	8137
507	S8R	1	8177	10177	10257	8257	9177	10217	9257	8217
508	S8R	1	8257	10257	10337	8337	9257	10297	9337	8297

S H E L L   S E C T I O N (S)

PROPERTY NUMBER 1

NUMBER OF INTEGRATION POINTS 13
NUMBER OF LAYERS 1

LAYER	THICKNESS	POINTS	MATERIAL	ORIENTATION
1	7.833	13	M1	

TRANSVERSE SHEAR STIFFNESSES FOR THE SECTION

K(13)	K(23)
5.02137E+05	5.02137E+05

60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING

```
PROPERTY NUMBER          2

   NUMBER OF INTEGRATION POINTS     5
   NUMBER OF LAYERS                 1

      LAYER   THICKNESS     POINTS   MATERIAL   ORIENTATION

        1       150.0          5       M2

   TRANSVERSE SHEAR STIFFNESSES FOR THE SECTION

     K(13)       K(23)

   9.61538E+06 9.61538E+06
```

M A T E R I A L   D E S C R I P T I O N

```
MATERIAL NAME: M1

   ELASTIC          YOUNGS     POISSONS
                    MODULUS     RATIO

                  2.00000E+05 0.30000

   PLASTICITY - MISES YIELD SURFACE WITH
                PERFECT PLASTICITY

                     STRESS

                    332.00

MATERIAL NAME: M2
```

ABAQUS PRODUCTION VERSION 4-7-22 DATE 5MAY 90 TIME 17:26:15 PAGE 19
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING

ELASTIC

YOUNGS MODULUS	POISSONS RATIO
2.00000E+05	0.30000

E L E M E N T   S E T S

SET	ANGLE	MEMBERS	101	102	103	104	105	106	107	109	201	202
			205	206	207	208	301	302	303	304	305	306
			401	402	403	404	405	406	407	408	501	502
			505	506	507	508						
SET	E1	MEMBERS	1	2	101	102	201	202	301	302	401	402
SET	E2	MEMBERS	3	4	103	104	203	204	303	304	403	404
SET	E3	MEMBERS	105	106	205	206	305	306	405	406	505	506
SET	E4	MEMBERS	107	108	207	208	307	308	407	408	507	508
SET	FIGURE	MEMBERS	1	2	3	4						
SET	PLATE	MEMBERS	1	2	3	4	11	12	13	14	21	22
			31	32	33	34	51	52	53	54	61	62
			71	72	73	74	81	82	83	84		

N O D E   S E T S

SET	D1	MEMBERS	1	3	5	7	9	11	13	15	17	
SET	D2	MEMBERS	161	163	165	167	169	171	173	175	177	
SET	D3	MEMBERS	321	323	325	327	329	331	333	335	337	
SET	D4	MEMBERS	1	3	5	7	9	11	13	15	17	41
			53	57	81	83	85	87	89	91	93	95
			125	129	133	137	161	163	165	167	169	171
			177									

ABAQUS PRODUCTION VERSION 4-7-22 DATE 5MAY 90 TIME 17:26:15 PAGE 19
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING

SET	DS	MEMBERS	161	163	165	167	169	171	173	175	177	201	2[illegible]
			213	217	241	243	245	247	249	251	253	255	2[illegible]
			285	289	293	297	321	323	325	327	329	331	3[illegible]
			337										
SET	BOT	MEMBERS	1	3	5	7	9	11	13	15	17	41	[illegible]
			53	57	81	83	85	87	89	91	93	95	[illegible]
			125	129	133	137	161	163	165	167	169	171	1[illegible]
			177	201	205	209	213	217	241	243	245	247	2[illegible]
			253	255	257	281	285	289	293	297	321	323	3[illegible]
			329	331	333	335	337						
SET	TOP	MEMBERS	10001	10003	10005	10007	10009	10011	10013	10015	10017	10041	100[illegible]
			10053	10057	10081	10083	10085	10087	10089	10091	10093	10095	100[illegible]
			10125	10129	10133	10137	10161	10163	10165	10167	10169	10171	101[illegible]
			10177	10201	10205	10209	10213	10217	10241	10243	10245	10247	102[illegible]
			10253	10255	10257	10281	10285	10289	10293	10297	10321	10323	101[illegible]
			10329	10331	10333	10335	10337						
SET	END1	MEMBERS	1	3	5	7	9	11	13	15	17	57	
			177	217	257	297	337						
SET	END2	MEMBERS	10001	10003	10005	10007	10009	10011	10013	10015	10017	10057	10[illegible]
			10177	10217	10257	10297	10337						
SET	JANGLE	MEMBERS	1	3	5	7	9	11	13	15	17	57	
			177	217	257	297	337	1001	1005	1009	1013	1017	1[illegible]
			1257	1337	2001	2003	2005	2007	2009	2011	2013	2015	201[illegible]
			2097	2137	2177	2217	2257	2297	2337	3001	3005	3009	301[illegible]
			3097	3177	3257	3337	4001	4003	4005	4007	4009	4011	401[illegible]
			4017	4057	4097	4137	4177	4217	4257	4297	4337	5001	50[illegible]
			5013	5017	5097	5177	5257	5337	6001	6003	6005	6007	60[illegible]
			6013	6015	6017	6057	6097	6137	6177	6217	6257	6297	63[illegible]
			7005	7009	7013	7017	7097	7177	7257	7337	8001	8003	[illegible]
			8009	8011	8013	8015	8017	8057	8097	8137	8177	8217	82[illegible]
			8337	9001	9005	9009	9013	9017	9097	9177	9257	9337	100[illegible]
			10005	10007	10009	10011	10013	10015	10017	10057	10097	10137	101[illegible]
			10257	10297	10337								

N O D E   D E F I N I T I O N S

NODE NUMBER	COORDINATES			NORMAL			SINGLE POINT CONSTRAINTS TYPE PLUS DOF
1	0.00000E+00	101.87	-65.112	1.0000	0.00000E+00	0.00000E+00	
3	0.00000E+00	80.127	-52.560	1.0000	0.00000E+00	0.00000E+00	

60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING

5	0.00000E+00	58.385	-40.007	1.0000	0.00000E+00	0.00000E+00
7	0.00000E+00	36.644	-27.455	1.0000	0.00000E+00	0.00000E+00
9	0.00000E+00	14.902	-14.902	1.0000	0.00000E+00	0.00000E+00
11	0.00000E+00	11.177	-11.177	1.0000	0.00000E+00	0.00000E+00
13	0.00000E+00	7.4511	-7.4511	1.0000	0.00000E+00	0.00000E+00
15	0.00000E+00	3.7256	-3.7256	1.0000	0.00000E+00	0.00000E+00
17	0.00000E+00	0.00000E+00	0.00000E+00	1.0000	0.00000E+00	0.00000E+00
41	0.00000E+00	108.06	-58.919	1.0000	0.00000E+00	0.00000E+00
45	0.00000E+00	65.813	-35.048	1.0000	0.00000E+00	0.00000E+00
49	0.00000E+00	23.564	-11.177	1.0000	0.00000E+00	0.00000E+00
53	0.00000E+00	13.545	-3.7256	1.0000	0.00000E+00	0.00000E+00
57	0.00000E+00	3.7256	3.7256	1.0000	0.00000E+00	0.00000E+00
81	0.00000E+00	114.26	-52.725	1.0000	0.00000E+00	0.00000E+00
83	0.00000E+00	93.749	-41.406	1.0000	0.00000E+00	0.00000E+00
85	0.00000E+00	73.241	-30.088	1.0000	0.00000E+00	0.00000E+00
87	0.00000E+00	52.734	-18.770	1.0000	0.00000E+00	0.00000E+00
89	0.00000E+00	32.226	-7.4511	1.0000	0.00000E+00	0.00000E+00
91	0.00000E+00	26.032	-3.7256	1.0000	0.00000E+00	0.00000E+00
93	0.00000E+00	19.839	2.22045E-16	1.0000	0.00000E+00	0.00000E+00
95	0.00000E+00	13.645	3.7256	1.0000	0.00000E+00	0.00000E+00
97	0.00000E+00	7.4511	7.4511	1.0000	0.00000E+00	0.00000E+00
121	0.00000E+00	120.45	-46.531	1.0000	0.00000E+00	0.00000E+00
125	0.00000E+00	80.669	-25.128	1.0000	0.00000E+00	0.00000E+00
129	0.00000E+00	40.888	-3.7256	1.0000	0.00000E+00	0.00000E+00
133	0.00000E+00	26.032	3.7256	1.0000	0.00000E+00	0.00000E+00
137	0.00000E+00	11.177	11.177	1.0000	0.00000E+00	0.00000E+00
161	0.00000E+00	126.64	-40.337	1.0000	0.00000E+00	0.00000E+00
163	0.00000E+00	107.37	-30.253	1.0000	0.00000E+00	0.00000E+00
165	0.00000E+00	88.097	-20.169	1.0000	0.00000E+00	0.00000E+00
167	0.00000E+00	68.823	-10.084	1.0000	0.00000E+00	0.00000E+00
169	0.00000E+00	49.550	0.00000E+00	1.0000	0.00000E+00	0.00000E+00
171	0.00000E+00	40.888	3.7256	1.0000	0.00000E+00	0.00000E+00
173	0.00000E+00	32.226	7.4511	1.0000	0.00000E+00	0.00000E+00
175	0.00000E+00	23.564	11.177	1.0000	0.00000E+00	0.00000E+00
177	0.00000E+00	14.902	14.902	1.0000	0.00000E+00	0.00000E+00
201	0.00000E+00	136.73	-30.253	1.0000	0.00000E+00	0.00000E+00
205	0.00000E+00	102.78	-10.084	1.0000	0.00000E+00	0.00000E+00
209	0.00000E+00	68.823	10.084	1.0000	0.00000E+00	0.00000E+00
213	0.00000E+00	52.734	18.770	1.0000	0.00000E+00	0.00000E+00
217	0.00000E+00	36.644	27.455	1.0000	0.00000E+00	0.00000E+00
241	0.00000E+00	146.81	-20.169	1.0000	0.00000E+00	0.00000E+00
243	0.00000E+00	132.13	-10.084	1.0000	0.00000E+00	0.00000E+00
245	0.00000E+00	117.45	0.00000E+00	1.0000	0.00000E+00	0.00000E+00
247	0.00000E+00	102.78	10.084	1.0000	0.00000E+00	0.00000E+00
249	0.00000E+00	88.097	20.169	1.0000	0.00000E+00	0.00000E+00
251	0.00000E+00	80.669	25.128	1.0000	0.00000E+00	0.00000E+00
253	0.00000E+00	73.241	30.088	1.0000	0.00000E+00	0.00000E+00
255	0.00000E+00	65.813	35.048	1.0000	0.00000E+00	0.00000E+00

1 2 3 4

60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING

257	0.00000E+00	58.385	40.007	1.0000	0.00000E+00	0.00000E+00
281	0.00000E+00	156.90	-10.084	1.0000	0.00000E+00	0.00000E+00
285	0.00000E+00	132.13	10.084	1.0000	0.00000E+00	0.00000E+00
289	0.00000E+00	107.37	30.253	1.0000	0.00000E+00	0.00000E+00
293	0.00000E+00	93.749	41.406	1.0000	0.00000E+00	0.00000E+00
297	0.00000E+00	80.127	52.560	1.0000	0.00000E+00	0.00000E+00
321	0.00000E+00	166.98	0.00000E+00	1.0000	0.00000E+00	0.00000E+00
323	0.00000E+00	156.90	10.084	1.0000	0.00000E+00	0.00000E+00
325	0.00000E+00	146.81	20.169	1.0000	0.00000E+00	0.00000E+00
327	0.00000E+00	136.73	30.253	1.0000	0.00000E+00	0.00000E+00
329	0.00000E+00	126.64	40.337	1.0000	0.00000E+00	0.00000E+00
331	0.00000E+00	120.45	46.531	1.0000	0.00000E+00	0.00000E+00
333	0.00000E+00	114.26	52.725	1.0000	0.00000E+00	0.00000E+00
335	0.00000E+00	108.06	58.919	1.0000	0.00000E+00	0.00000E+00
337	0.00000E+00	101.87	65.112	1.0000	0.00000E+00	0.00000E+00
1001	165.42	101.87	-65.112	0.00000E+00	-0.50000	-0.86603
1005	165.42	58.385	-40.007	0.00000E+00	-0.50000	-0.86603
1009	165.42	14.902	-14.902	0.00000E+00	-0.60876	-0.79335
1013	165.42	7.4511	-7.4511	0.00000E+00	-0.70711	-0.70711
1017	165.42	0.00000E+00	0.00000E+00	0.00000E+00	-0.70711	-0.70711
1097	165.42	7.4511	7.4511	0.00000E+00	-0.70711	0.70711
1177	165.42	14.902	14.902	0.00000E+00	-0.60876	0.79335
1257	165.42	58.385	40.007	0.00000E+00	-0.50000	0.86603
1337	165.42	101.87	65.112	0.00000E+00	-0.50000	0.86603
2001	330.83	101.87	-65.112	0.00000E+00	-0.50000	-0.86603
2003	330.83	80.127	-52.560	0.00000E+00	-0.50000	-0.86603
2005	330.83	58.385	-40.007	0.00000E+00	-0.50000	-0.86603
2007	330.83	36.644	-27.455	0.00000E+00	-0.50000	-0.86603
2009	330.83	14.902	-14.902	0.00000E+00	-0.60876	-0.79335
2011	330.83	11.177	-11.177	0.00000E+00	-0.70711	-0.70711
2013	330.83	7.4511	-7.4511	0.00000E+00	-0.70711	-0.70711
2015	330.83	3.7256	-3.7256	0.00000E+00	-0.70711	-0.70711
2017	330.83	0.00000E+00	0.00000E+00	0.00000E+00	-0.70711	-0.70711
2057	330.83	3.7256	3.7256	0.00000E+00	-0.70711	0.70711
2097	330.83	7.4511	7.4511	0.00000E+00	-0.70711	0.70711
2137	330.83	11.177	11.177	0.00000E+00	-0.70711	0.70711
2177	330.83	14.902	14.902	0.00000E+00	-0.60876	0.79335
2217	330.83	36.644	27.455	0.00000E+00	-0.50000	0.86603
2257	330.83	58.385	40.007	0.00000E+00	-0.50000	0.86603
2297	330.83	80.127	52.560	0.00000E+00	-0.50000	0.86603
2337	330.83	101.87	65.112	0.00000E+00	-0.50000	0.86603
3001	496.25	101.87	-65.112	0.00000E+00	-0.50000	-0.86603
3005	496.25	58.385	-40.007	0.00000E+00	-0.50000	-0.86603
3009	496.25	14.902	-14.902	0.00000E+00	-0.60876	-0.79335
3013	496.25	7.4511	-7.4511	0.00000E+00	-0.70711	-0.70711
3017	496.25	0.00000E+00	0.00000E+00	0.00000E+00	-0.70711	-0.70711
3097	496.25	7.4511	7.4511	0.00000E+00	-0.70711	0.70711
3177	496.25	14.902	14.902	0.00000E+00	-0.60876	0.79335

ABAQUS PRODUCTION VERSION 4-7-22 DATE 5MAY 90 TIME 17:26:15 PAGE 22
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING

3257	496.25	58.385	40.007	0.00000E+00-0.50000	0.86603
3337	496.25	101.87	65.112	0.00000E+00-0.50000	0.86603
4001	661.67	101.87	-65.112	0.00000E+00-0.50000	-0.86603
4003	661.67	80.127	-52.560	0.00000E+00-0.50000	-0.86603
4005	661.67	58.385	-40.007	0.00000E+00-0.50000	-0.86603
4007	661.67	36.644	-27.455	0.00000E+00-0.50000	-0.86603
4009	661.67	14.902	-14.902	0.00000E+00-0.60876	-0.79335
4011	661.67	11.177	-11.177	0.00000E+00-0.70711	-0.70711
4013	661.67	7.4511	-7.4511	0.00000E+00-0.70711	-0.70711
4015	661.67	3.7256	-3.7256	0.00000E+00-0.70711	-0.70711
4017	661.67	0.00000E+00	0.00000E+00	0.00000E+00-0.70711	-0.70711
4057	661.67	3.7256	3.7256	0.00000E+00-0.70711	0.70711
4097	661.67	7.4511	7.4511	0.00000E+00-0.70711	0.70711
4137	661.67	11.177	11.177	0.00000E+00-0.70711	0.70711
4177	661.67	14.902	14.902	0.00000E+00-0.60876	0.79335
4217	661.67	36.644	27.455	0.00000E+00-0.50000	0.86603
4257	661.67	58.385	40.007	0.00000E+00-0.50000	0.86603
4297	661.67	80.127	52.560	0.00000E+00-0.50000	0.86603
4337	661.67	101.87	65.112	0.00000E+00-0.50000	0.86603
5001	827.09	101.87	-65.112	0.00000E+00-0.50000	-0.86603
5005	827.09	58.385	-40.007	0.00000E+00-0.50000	-0.86603
5009	827.09	14.902	-14.902	0.00000E+00-0.60876	-0.79335
5013	827.09	7.4511	-7.4511	0.00000E+00-0.70711	-0.70711
5017	827.09	0.00000E+00	0.00000E+00	0.00000E+00-0.70711	-0.70711
5097	827.09	7.4511	7.4511	0.00000E+00-0.70711	0.70711
5177	827.09	14.902	14.902	0.00000E+00-0.60876	0.79335
5257	827.09	58.385	40.007	0.00000E+00-0.50000	0.86603
5337	827.09	101.87	65.112	0.00000E+00-0.50000	0.86603
6001	992.50	101.87	-65.112	0.00000E+00-0.50000	-0.86603
6003	992.50	80.127	-52.560	0.00000E+00-0.50000	-0.86603
6005	992.50	58.385	-40.007	0.00000E+00-0.50000	-0.86603
6007	992.50	36.644	-27.455	0.00000E+00-0.50000	-0.86603
6009	992.50	14.902	-14.902	0.00000E+00-0.60876	-0.79335
6011	992.50	11.177	-11.177	0.00000E+00-0.70711	-0.70711
6013	992.50	7.4511	-7.4511	0.00000E+00-0.70711	-0.70711
6015	992.50	3.7256	-3.7256	0.00000E+00-0.70711	-0.70711
6017	992.50	0.00000E+00	0.00000E+00	0.00000E+00-0.70711	-0.70711
6057	992.50	3.7256	3.7256	0.00000E+00-0.70711	0.70711
6097	992.50	7.4511	7.4511	0.00000E+00-0.70711	0.70711
6137	992.50	11.177	11.177	0.00000E+00-0.70711	0.70711
6177	992.50	14.902	14.902	0.00000E+00-0.60876	0.79335
6217	992.50	36.644	27.455	0.00000E+00-0.50000	0.86603
6257	992.50	58.385	40.007	0.00000E+00-0.50000	0.86603
6297	992.50	80.127	52.560	0.00000E+00-0.50000	0.86603
6337	992.50	101.87	65.112	0.00000E+00-0.50000	0.86603
7001	1157.9	101.87	-65.112	0.00000E+00-0.50000	-0.86603
7005	1157.9	58.385	-40.007	0.00000E+00-0.50000	-0.86603
7009	1157.9	14.902	-14.902	0.00000E+00-0.60876	-0.79335

60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING

7013	1157.9	7.4511	-7.4511	0.00000E+00	-0.70711	-0.70711
7017	1157.9	0.00000E+00	0.00000E+00	0.00000E+00	-0.70711	-0.70711
7097	1157.9	7.4511	7.4511	0.00000E+00	-0.70711	0.70711
7177	1157.9	14.902	14.902	0.00000E+00	-0.60876	0.79335
7257	1157.9	58.385	40.007	0.00000E+00	-0.50000	0.86603
7337	1157.9	101.87	65.112	0.00000E+00	-0.50000	0.86603
8001	1323.3	101.87	-65.112	0.00000E+00	-0.50000	-0.86603
8003	1323.3	80.127	-52.560	0.00000E+00	-0.50000	-0.86603
8005	1323.3	58.385	-40.007	0.00000E+00	-0.50000	-0.86603
8007	1323.3	36.644	-27.455	0.00000E+00	-0.50000	-0.86603
8009	1323.3	14.902	-14.902	0.00000E+00	-0.60876	-0.79335
8011	1323.3	11.177	-11.177	0.00000E+00	-0.70711	-0.70711
8013	1323.3	7.4511	-7.4511	0.00000E+00	-0.70711	-0.70711
8015	1323.3	3.7256	-3.7256	0.00000E+00	-0.70711	-0.70711
8017	1323.3	0.00000E+00	0.00000E+00	0.00000E+00	-0.70711	-0.70711
8057	1323.3	3.7256	3.7256	0.00000E+00	-0.70711	0.70711
8097	1323.3	7.4511	7.4511	0.00000E+00	-0.70711	0.70711
8137	1323.3	11.177	11.177	0.00000E+00	-0.70711	0.70711
8177	1323.3	14.902	14.902	0.00000E+00	-0.60876	0.79335
8217	1323.3	36.644	27.455	0.00000E+00	-0.50000	0.86603
8257	1323.3	58.385	40.007	0.00000E+00	-0.50000	0.86603
8297	1323.3	80.127	52.560	0.00000E+00	-0.50000	0.86603
8337	1323.3	101.87	65.112	0.00000E+00	-0.50000	0.86603
9001	1488.8	101.87	-65.112	0.00000E+00	-0.50000	-0.86603
9005	1488.8	58.385	-40.007	0.00000E+00	-0.50000	-0.86603
9009	1488.8	14.902	-14.902	0.00000E+00	-0.60876	-0.79335
9013	1488.8	7.4511	-7.4511	0.00000E+00	-0.70711	-0.70711
9017	1488.8	0.00000E+00	0.00000E+00	0.00000E+00	-0.70711	-0.70711
9097	1488.8	7.4511	7.4511	0.00000E+00	-0.70711	0.70711
9177	1488.8	14.902	14.902	0.00000E+00	-0.60876	0.79335
9257	1488.8	58.385	40.007	0.00000E+00	-0.50000	0.86603
9337	1488.8	101.87	65.112	0.00000E+00	-0.50000	0.86603
10001	1654.2	101.87	-65.112	1.0000	0.00000E+00	0.00000E+00
10003	1654.2	80.127	-52.560	1.0000	0.00000E+00	0.00000E+00
10005	1654.2	58.385	-40.007	1.0000	0.00000E+00	0.00000E+00
10007	1654.2	36.644	-27.455	1.0000	0.00000E+00	0.00000E+00
10009	1654.2	14.902	-14.902	1.0000	0.00000E+00	0.00000E+00
10011	1654.2	11.177	-11.177	1.0000	0.00000E+00	0.00000E+00
10013	1654.2	7.4511	-7.4511	1.0000	0.00000E+00	0.00000E+00
10015	1654.2	3.7256	-3.7256	1.0000	0.00000E+00	0.00000E+00
10017	1654.2	0.00000E+00	0.00000E+00	1.0000	0.00000E+00	0.00000E+00
10041	1654.2	108.06	-58.919	1.0000	0.00000E+00	0.00000E+00
10045	1654.2	65.813	-35.048	1.0000	0.00000E+00	0.00000E+00
10049	1654.2	23.564	-11.177	1.0000	0.00000E+00	0.00000E+00
10053	1654.2	13.645	-3.7256	1.0000	0.00000E+00	0.00000E+00
10057	1654.2	3.7256	3.7256	1.0000	0.00000E+00	0.00000E+00
10081	1654.2	114.26	-52.725	1.0000	0.00000E+00	0.00000E+00
10083	1654.2	93.749	-41.406	1.0000	0.00000E+00	0.00000E+00

60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING

10085	1654.2	73.241	-30.088	1.0000	0.00000E+00	0.00000E+00
10087	1654.2	52.734	-18.770	1.0000	0.00000E+00	0.00000E+00
10089	1654.2	32.226	-7.4511	1.0000	0.00000E+00	0.00000E+00
10091	1654.2	26.032	-3.7256	1.0000	0.00000E+00	0.00000E+00
10093	1654.2	19.839	2.22045E-16	1.0000	0.00000E+00	0.00000E+00
10095	1654.2	13.645	3.7256	1.0000	0.00000E+00	0.00000E+00
10097	1654.2	7.4511	7.4511	1.0000	0.00000E+00	0.00000E+00
10121	1654.2	120.45	-46.531	1.0000	0.00000E+00	0.00000E+00
10125	1654.2	80.669	-25.128	1.0000	0.00000E+00	0.00000E+00
10129	1654.2	40.888	-3.7256	1.0000	0.00000E+00	0.00000E+00
10133	1654.2	26.032	3.7256	1.0000	0.00000E+00	0.00000E+00
10137	1654.2	11.177	11.177	1.0000	0.00000E+00	0.00000E+00
10161	1654.2	126.64	-40.337	1.0000	0.00000E+00	0.00000E+00
10163	1654.2	107.37	-30.253	1.0000	0.00000E+00	0.00000E+00
10165	1654.2	88.097	-20.169	1.0000	0.00000E+00	0.00000E+00
10167	1654.2	68.823	-10.084	1.0000	0.00000E+00	0.00000E+00
10169	1654.2	49.550	0.00000E+00	1.0000	0.00000E+00	0.00000E+00
10171	1654.2	40.888	3.7256	1.0000	0.00000E+00	0.00000E+00
10173	1654.2	32.226	7.4511	1.0000	0.00000E+00	0.00000E+00
10175	1654.2	23.564	11.177	1.0000	0.00000E+00	0.00000E+00
10177	1654.2	14.902	14.902	1.0000	0.00000E+00	0.00000E+00
10201	1654.2	136.73	-30.253	1.0000	0.00000E+00	0.00000E+00
10205	1654.2	102.78	-10.084	1.0000	0.00000E+00	0.00000E+00
10209	1654.2	68.823	10.084	1.0000	0.00000E+00	0.00000E+00
10213	1654.2	52.734	18.770	1.0000	0.00000E+00	0.00000E+00
10217	1654.2	36.644	27.455	1.0000	0.00000E+00	0.00000E+00
10241	1654.2	146.81	-20.169	1.0000	0.00000E+00	0.00000E+00
10243	1654.2	132.13	-10.084	1.0000	0.00000E+00	0.00000E+00
10245	1654.2	117.45	0.00000E+00	1.0000	0.00000E+00	0.00000E+00
10247	1654.2	102.78	10.084	1.0000	0.00000E+00	0.00000E+00
10249	1654.2	88.097	20.169	1.0000	0.00000E+00	0.00000E+00
10251	1654.2	80.669	25.128	1.0000	0.00000E+00	0.00000E+00
10253	1654.2	73.241	30.088	1.0000	0.00000E+00	0.00000E+00
10255	1654.2	65.813	35.048	1.0000	0.00000E+00	0.00000E+00
10257	1654.2	58.385	40.007	1.0000	0.00000E+00	0.00000E+00
10281	1654.2	156.90	-10.084	1.0000	0.00000E+00	0.00000E+00
10285	1654.2	132.13	10.084	1.0000	0.00000E+00	0.00000E+00
10289	1654.2	107.37	30.253	1.0000	0.00000E+00	0.00000E+00
10293	1654.2	93.749	41.406	1.0000	0.00000E+00	0.00000E+00
10297	1654.2	80.127	52.560	1.0000	0.00000E+00	0.00000E+00
10321	1654.2	166.98	0.00000E+00	1.0000	0.00000E+00	0.00000E+00
10323	1654.2	156.90	10.084	1.0000	0.00000E+00	0.00000E+00
10325	1654.2	146.81	20.169	1.0000	0.00000E+00	0.00000E+00
10327	1654.2	136.73	30.253	1.0000	0.00000E+00	0.00000E+00
10329	1654.2	126.64	40.337	1.0000	0.00000E+00	0.00000E+00
10331	1654.2	120.45	46.531	1.0000	0.00000E+00	0.00000E+00
10333	1654.2	114.26	52.725	1.0000	0.00000E+00	0.00000E+00
10335	1654.2	108.06	58.919	1.0000	0.00000E+00	0.00000E+00

2 3 4

ABAQUS PRODUCTION VERSION 4-7-22 DATE 5MAY 90 TIME 17:26:15 PAGE 25
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
10337 1654.2 101.87 65.112 1.0000 0.00000E+00 0.00000E+00

N O R M A L   D E F I N I T I O N S

ELEMENT	NODE	NORMAL		
101	1	0.0000E+00	-0.5000	-0.8660
101	3	0.0000E+00	-0.5000	-0.8660
102	9	0.0000E+00	-0.6088	-0.7934
103	9	0.0000E+00	-0.6088	-0.7934
103	11	0.0000E+00	-0.7071	-0.7071
104	17	0.0000E+00	-0.7071	-0.7071
105	17	0.0000E+00	-0.7071	0.7071
105	97	0.0000E+00	-0.7071	0.7071
105	57	0.0000E+00	-0.7071	0.7071
106	177	0.0000E+00	-0.6088	0.7934
107	177	0.0000E+00	-0.6088	0.7934
107	217	0.0000E+00	-0.5000	0.8660
108	337	0.0000E+00	-0.5000	0.8660
205	2017	0.0000E+00	-0.7071	0.7071
205	3017	0.0000E+00	-0.7071	0.7071
305	6017	0.0000E+00	-0.7071	0.7071
405	6017	0.0000E+00	-0.7071	0.7071
405	7017	0.0000E+00	-0.7071	0.7071
501	10005	0.0000E+00	-0.5000	-0.8660
502	10005	0.0000E+00	-0.5000	-0.8660
502	10007	0.0000E+00	-0.5000	-0.8660
503	10013	0.0000E+00	-0.7071	-0.7071
504	10013	0.0000E+00	-0.7071	-0.7071
504	10015	0.0000E+00	-0.7071	-0.7071
505	10017	0.0000E+00	-0.7071	0.7071
505	9017	0.0000E+00	-0.7071	0.7071
506	10097	0.0000E+00	-0.7071	0.7071
506	10137	0.0000E+00	-0.7071	0.7071
507	10257	0.0000E+00	-0.5000	0.8660
508	10257	0.0000E+00	-0.5000	0.8660
508	10297	0.0000E+00	-0.5000	0.8660

ELEMENT	NODE	NORMAL		
101	5	0.0000E+00	-0.5000	-0.8660
102	5	0.0000E+00	-0.5000	-0.8660
102	7	0.0000E+00	-0.5000	-0.8660
103	13	0.0000E+00	-0.7071	-0.7071
104	13	0.0000E+00	-0.7071	-0.7071
104	15	0.0000E+00	-0.7071	-0.7071
105	2017	0.0000E+00	-0.7071	0.7071
105	1017	0.0000E+00	-0.7071	0.7071
106	97	0.0000E+00	-0.7071	0.7071
106	137	0.0000E+00	-0.7071	0.7071
107	257	0.0000E+00	-0.5000	0.8660
108	257	0.0000E+00	-0.5000	0.8660
108	297	0.0000E+00	-0.5000	0.8660
205	4017	0.0000E+00	-0.7071	0.7071
305	4017	0.0000E+00	-0.7071	0.7071
305	5017	0.0000E+00	-0.7071	0.7071
405	8017	0.0000E+00	-0.7071	0.7071
501	10001	0.0000E+00	-0.5000	-0.8660
501	10003	0.0000E+00	-0.5000	-0.8660
502	10009	0.0000E+00	-0.6088	-0.7934
503	10009	0.0000E+00	-0.6088	-0.7934
503	10011	0.0000E+00	-0.7071	-0.7071
504	10017	0.0000E+00	-0.7071	-0.7071
505	8017	0.0000E+00	-0.7071	0.7071
505	10097	0.0000E+00	-0.7071	0.7071
505	10057	0.0000E+00	-0.7071	0.7071
506	10177	0.0000E+00	-0.6088	0.7934
507	10177	0.0000E+00	-0.6088	0.7934
507	10217	0.0000E+00	-0.5000	0.8660
508	10337	0.0000E+00	-0.5000	0.8660

```
ABAQUS PRODUCTION VERSION 4-7-22                    DATE  5MAY 90      TIME 17:26:15        PAGE   26
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

 60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING

                          I N I T I A L   S T R E S S E S

 (NOT INCLUDING STRESSES DEFINED IN USER SUBROUTINE SIGINI)

 ELEMENT  INT.PT.  REBAR          STRESSES
 NUMBER            NAME
```

```
 ABAQUS PRODUCTION VERSION 4-7-22                        DATE  5MAY 90     TIME 17:26:15        PAGE   27
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

 60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING

                    S T E P      1     S T A T I C   A N A L Y S I S


 AUTOMATIC TIME CONTROL WITH -
      A SUGGESTED INITIAL TIME INCREMENT OF                    1.00
      AND A TOTAL TIME PERIOD OF                               1.00
      THE MINIMUM TIME INCREMENT ALLOWED IS                   1.000E-05
      THE MAXIMUM TIME INCREMENT ALLOWED IS                    1.00

 THE CONVERGENCE TOLERANCE MEASURES ARE -
      TOLERANCE ON INDIVIDUAL FORCE COMPONENTS                 200.
      TOLERANCE ON INDIVIDUAL MOMENT COMPONENTS                200.

      THE MAXIMUM NUMBER OF INCREMENTS IN THIS STEP IS               10
      THE MAXIMUM NUMBER OF ITERATIONS PER INCREMENT IS               6

      LARGE DISPLACEMENT THEORY WILL BE USED

 PRINT OF INCREMENT NUMBER, TIME, ETC., EVERY     1  INCREMENTS
```

```
ABAQUS PRODUCTION VERSION 4-7-22                          DATE  5MAY 90      TIME 17:26:15         PAGE   28
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

 60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING


                                    N O D E   P R I N T


THE FOLLOWING TABLE IS PRINTED FOR ALL NODES AT EVERY      1   INCREMENT

   SUMMARIES WILL BE PRINTED

       TABLE  1  RF1       RF2       RF3       RM1       RM2       RM3


                                    P L O T   O U T P U T

PLOT FRAME     1  CONSISTS OF ELSET  ANGLE

                  THE FRAME WILL BE GENERATED EVERY      1  INCREMENTS

                  TITLE -  60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
                  NUMBER OF COLORS AVAILABLE        1

                  ALL SIZES ARE IN PLOTTER UNITS                      X-DIRECTION  Y-DIRECTION

                  FRAME SIZE                                            10.000       10.000
                  PICTURE SIZE                                          7.0000       7.0000
                  POSITION OF LOWER LEFT HAND CORNER OF PICTURE         3.0000       2.0000
                  POSITION OF START OF TITLE                            1.5000       1.0000
                  POSITION OF UPPER LEFT HAND CORNER OF VARIABLE LIST  0.10000       8.0000
                  POSITION OF AXIS                                      1.5000       1.5000

                  SIZE OF CHARACTERS                                         0.16000
                  WIDTH OF PAPER STRIP BETWEEN FRAMES                         5.0000

                  MODEL AXIS ROTATION      0.785       0.000E+00   0.000E+00
```

ABAQUS PRODUCTION VERSION 4-7-22 DATE 5MAY 90 TIME 17:26:15 PAGE 29
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
DISPLACED SHAPE OF U WILL BE DRAWN
THE UNDEFORMED CONFIGURATION WILL BE DRAWN IN DOTTED LINES

B O U N D A R Y   C O N D I T I O N S

NODE	DOF	AMP. REF.	MAGNITUDE	NODE	DOF	AMP. REF.	MAGNITUDE
169	1		0.00000E+00	169	2		0.00000E+00
169	3		0.00000E+00	169	4		0.00000E+00
10169	2		0.00000E+00	10169	3		0.00000E+00
10169	4		0.00000E+00				

C O N C E N T R A T E D   L O A D S

NODE	DOF	AMP. REF.	AMPLITUDE	NODE	DOF	AMP. REF.	AMPLITUDE	NODE	DOF	AMP. REF.	[illegible]
169	6		-500.00	169	5		-500.00	10169	6		5[illegible]
10169	5		500.00								

```
ABAQUS PRODUCTION VERSION 4-7-22                          DATE  5MAY 90     TIME 17:26:15        PAGE   30
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING

              S T E P     2     S T A T I C   A N A L Y S I S


AUTOMATIC TIME CONTROL WITH -
     A SUGGESTED INITIAL TIME INCREMENT OF                    1.000E-01
     AND A TOTAL TIME PERIOD OF                                1.00
     THE MINIMUM TIME INCREMENT ALLOWED IS                    1.000E-03
     THE MAXIMUM TIME INCREMENT ALLOWED IS                    1.000E-01

THE CONVERGENCE TOLERANCE MEASURES ARE -
     TOLERANCE ON INDIVIDUAL FORCE COMPONENTS                  500.
     TOLERANCE ON INDIVIDUAL MOMENT COMPONENTS                 500.

     THE MAXIMUM NUMBER OF INCREMENTS IN THIS STEP IS             500
     THE MAXIMUM NUMBER OF ITERATIONS PER INCREMENT IS              6

     LARGE DISPLACEMENT THEORY WILL BE USED

PRINTOUT OF RESIDUALS DURING EQUILIBRIUM ITERATION IS SUPPRESSED

PRINT OF INCREMENT NUMBER, TIME, ETC., EVERY     1  INCREMENTS
```

```
ABAQUS PRODUCTION VERSION 4-7-22                    DATE  5MAY 90      TIME 17:26:15        PAGE   31
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

 60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING


                              E L E M E N T   P R I N T

THE FOLLOWING TABLE IS PRINTED FOR ALL ELEMENTS WITH TYPE S8R       AT EVERY     2  INCREMENT AT THE INTEGRATION

   VALUES ARE PRINTED  AT THE FOLLOWING BEAM/SHELL SECTION POINTS     1    5
   SUMMARIES WILL BE PRINTED
        TABLE    1  S11        S22        S12        MISES

THE FOLLOWING TABLE IS PRINTED FOR ALL ELEMENTS WITH TYPE S8R       AT EVERY     2  INCREMENT AT THE INTEGRATION

   VALUES ARE PRINTED  AT THE FOLLOWING BEAM/SHELL SECTION POINTS     1   13
   SUMMARIES WILL BE PRINTED
        TABLE    2  S11        S22        S12        MISES

THE FOLLOWING TABLE IS PRINTED FOR ALL ELEMENTS WITH TYPE S8R       AT EVERY     2  INCREMENT AT THE INTEGRATION

   VALUES ARE PRINTED  AT THE FOLLOWING BEAM/SHELL SECTION POINTS     1    5
   SUMMARIES WILL BE PRINTED
        TABLE    3  E11        E22        E12

THE FOLLOWING TABLE IS PRINTED FOR ALL ELEMENTS WITH TYPE S8R       AT EVERY     2  INCREMENT AT THE INTEGRATION

   VALUES ARE PRINTED  AT THE FOLLOWING BEAM/SHELL SECTION POINTS     1   13
   SUMMARIES WILL BE PRINTED
        TABLE    4  E11        E22        E12
```

```
ABAQUS PRODUCTION VERSION 4-7-22                              DATE  5MAY 90      TIME 17:26:15        PAGE   32
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM "KS, INC.

60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING

THE FOLLOWING TABLE IS PRINTED FOR ALL ELEMENTS WITH TYPE S8R      AT EVERY     2  INCREMENT AT THE INTEGRATION

   VALUES ARE PRINTED  AT THE FOLLOWING BEAM/SHELL SECTION POINTS     1     5
   SUMMARIES WILL BE PRINTED
       TABLE   5  IE11      IE22      IE12      PEMAG

THE FOLLOWING TABLE IS PRINTED FOR ALL ELEMENTS WITH TYPE S8R      AT EVERY     2  INCREMENT AT THE INTEGRATION

   VALUES ARE PRINTED  AT THE FOLLOWING BEAM/SHELL SECTION POINTS     1    13
   SUMMARIES WILL BE PRINTED
       TABLE    6  IE11      IE22      IE12      PEMAG


                              N O D E   P R I N T

THE FOLLOWING TABLE IS PRINTED FOR ALL NODES AT EVERY      1    INCREMENT

   SUMMARIES WILL BE PRINTED
       TABLE  1  U1        U2        U3        UR1       UR2       UR3

THE FOLLOWING TABLE IS PRINTED FOR ALL NODES AT EVERY      1    INCREMENT

   SUMMARIES WILL BE PRINTED
       TABLE  2  RF1       RF2       RF3       RM1       RM2       RM3
```

```
  ABAQUS PRODUCTION VERSION 4-7-22                                DATE  5MAY 90      TIME 17:26:15        PAGE    33
 FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

  60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING


THE FOLLOWING TABLE IS PRINTED FOR ALL NODES AT EVERY     1   INCREMENT

  SUMMARIES WILL BE PRINTED

      TABLE  3  CF1       CF2       CF3       CM1       CM2       CM3

THE FOLLOWING TABLE IS PRINTED FOR ALL NODES AT EVERY     1   INCREMENT

  SUMMARIES WILL BE PRINTED

      TABLE  4  RF1       RF2       RF3       RM1       RM2       RM3


                                    P L O T   O U T P U T


PLOT FRAME     1  CONSISTS OF ELSET  E1

                  THE FRAME WILL BE GENERATED EVERY     3  INCREMENTS

                  TITLE -  60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
                  NUMBER OF COLORS AVAILABLE      1

                  ALL SIZES ARE IN PLOTTER UNITS                           X-DIRECTION  Y-DIRECTION

                  FRAME SIZE                                                 10.000       10.000
                  PICTURE SIZE                                               7.0000       7.0000
                  POSITION OF LOWER LEFT HAND CORNER OF PICTURE              3.0000       2.0000
                  POSITION OF START OF TITLE                                 1.5000       1.0000
                  POSITION OF UPPER LEFT HAND CORNER OF VARIABLE LIST       0.10000       8.0000
                  POSITION OF AXIS                                           1.5000       1.5000

                  SIZE OF CHARACTERS                                             0.16000
                  WIDTH OF PAPER STRIP BETWEEN FRAMES                             5.0000
```

```
  ABAQUS PRODUCTION VERSION 4-7-22                              DATE  5MAY 90     TIME 17:26:15        PAGE   34
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

  60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
             MODEL AXIS ROTATION       0.524        0.000E+00   0.000E+00

             CONTOURS OF  S11        ARE PLOTTED
             NUMBER OF CONTOURS     4
             FACE NUMBER            1
             SECTION POINT          1
             ONLY THE OUTSIDE OF THE MESH WILL BE PLOTTED


PLOT FRAME    2  CONSISTS OF ELSET  E2

             THE FRAME WILL BE GENERATED EVERY     3  INCREMENTS

             TITLE -  60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
             NUMBER OF COLORS AVAILABLE      1

             ALL SIZES ARE IN PLOTTER UNITS                          X-DIRECTION  Y-DIRECTION

             FRAME SIZE                                                10.000      10.000
             PICTURE SIZE                                              7.0000      7.0000
             POSITION OF LOWER LEFT HAND CORNER OF PICTURE             3.0000      2.0000
             POSITION OF START OF TITLE                                1.5000      1.0000
             POSITION OF UPPER LEFT HAND CORNER OF VARIABLE LIST      0.10000      8.0000
             POSITION OF AXIS                                          1.5000      1.5000

             SIZE OF CHARACTERS                                            0.16000
             WIDTH OF PAPER STRIP BETWEEN FRAMES                            5.0000

             MODEL AXIS ROTATION       0.785        0.000E+00   0.000E+00


             CONTOURS OF  S11        ARE PLOTTED
             NUMBER OF CONTOURS     4
             FACE NUMBER            1
             SECTION POINT          1
             ONLY THE OUTSIDE OF THE MESH WILL BE PLOTTED


PLOT FRAME    3  CONSISTS OF ELSET  E3

             THE FRAME WILL BE GENERATED EVERY     3  INCREMENTS

             TITLE -  60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
             NUMBER OF COLORS AVAILABLE      1
```

```
60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING

              ALL SIZES ARE IN PLOTTER UNITS                          X-DIRECTION  Y-DIRECTION

              FRAME SIZE                                                 10.000       10.000
              PICTURE SIZE                                               7.0000       7.0000
              POSITION OF LOWER LEFT HAND CORNER OF PICTURE              3.0000       2.0000
              POSITION OF START OF TITLE                                 1.5000       1.0000
              POSITION OF UPPER LEFT HAND CORNER OF VARIABLE LIST       0.10000       8.0000
              POSITION OF AXIS                                           1.5000       1.5000

              SIZE OF CHARACTERS                                            0.16000
              WIDTH OF PAPER STRIP BETWEEN FRAMES                            5.0000

              MODEL AXIS ROTATION       2.36       0.000E+00    0.000E+00


              CONTOURS OF   S11       ARE PLOTTED
              NUMBER OF CONTOURS     4
              FACE NUMBER            1
              SECTION POINT          1
              ONLY THE OUTSIDE OF THE MESH WILL BE PLOTTED


PLOT FRAME    4  CONSISTS OF ELSET  E4

              THE FRAME WILL BE GENERATED EVERY     3  INCREMENTS

              TITLE -  60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
              NUMBER OF COLORS AVAILABLE      1

              ALL SIZES ARE IN PLOTTER UNITS                          X-DIRECTION  Y-DIRECTION

              FRAME SIZE                                                 10.000       10.000
              PICTURE SIZE                                               7.0000       7.0000
              POSITION OF LOWER LEFT HAND CORNER OF PICTURE              3.0000       2.0000
              POSITION OF START OF TITLE                                 1.5000       1.0000
              POSITION OF UPPER LEFT HAND CORNER OF VARIABLE LIST       0.10000       8.0000
              POSITION OF AXIS                                           1.5000       1.5000

              SIZE OF CHARACTERS                                            0.16000
              WIDTH OF PAPER STRIP BETWEEN FRAMES                            5.0000

              MODEL AXIS ROTATION       2.62       0.000E+00    0.000E+00
```

```
                                                            DATE  5MAY 90      TIME 17:26:15        PAGE   36
 ABAQUS PRODUCTION VERSION 4-7-22
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

 60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING

              CONTOURS OF  S11        ARE PLOTTED
              NUMBER OF CONTOURS      4
              FACE NUMBER             1
              SECTION POINT           1
              ONLY THE OUTSIDE OF THE MESH WILL BE PLOTTED


PLOT FRAME    5  CONSISTS OF ELSET  ANGLE

              THE FRAME WILL BE GENERATED EVERY     3  INCREMENTS

              TITLE -  60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
              NUMBER OF COLORS AVAILABLE      1
                                                                   X-DIRECTION  Y-DIRECTION
              ALL SIZES ARE IN PLOTTER UNITS
                                                                     10.000      10.000
              FRAME SIZE                                             7.0000      7.0000
              PICTURE SIZE                                           3.0000      2.0000
              POSITION OF LOWER LEFT HAND CORNER OF PICTURE          1.5000      1.0000
              POSITION OF START OF TITLE                            0.10000      8.0000
              POSITION OF UPPER LEFT HAND CORNER OF VARIABLE LIST    1.5000      1.5000
              POSITION OF AXIS
                                                                         0.16000
              SIZE OF CHARACTERS                                          5.0000
              WIDTH OF PAPER STRIP BETWEEN FRAMES

              DISPLACED SHAPE OF  U       WILL BE DRAWN
              THE UNDEFORMED CONFIGURATION WILL BE DRAWN IN DOTTED LINES


PLOT FRAME    6  CONSISTS OF ELSET  ANGLE

              THE FRAME WILL BE GENERATED EVERY     3  INCREMENTS

              TITLE -  60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
              NUMBER OF COLORS AVAILABLE      1
                                                                   X-DIRECTION  Y-DIRECTION
              ALL SIZES ARE IN PLOTTER UNITS
                                                                     10.000      10.000
              FRAME SIZE                                             7.0000      7.0000
              PICTURE SIZE                                           3.0000      2.0000
              POSITION OF LOWER LEFT HAND CORNER OF PICTURE          1.5000      1.0000
              POSITION OF START OF TITLE                            0.10000      8.0000
              POSITION OF UPPER LEFT HAND CORNER OF VARIABLE LIST    1.5000      1.5000
              POSITION OF AXIS
```

```
 60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
            SIZE OF CHARACTERS                                     0.16000
            WIDTH OF PAPER STRIP BETWEEN FRAMES                     5.0000

            MODEL AXIS ROTATION      1.57      0.000E+00   0.000E+00

            DISPLACED SHAPE OF  U       WILL BE DRAWN
            THE UNDEFORMED CONFIGURATION WILL BE DRAWN IN DOTTED LINES


PLOT FRAME    7 CONSISTS OF ELSET  ANGLE

            THE FRAME WILL BE GENERATED EVERY     3  INCREMENTS

            TITLE -  60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
            NUMBER OF COLORS AVAILABLE      1

            ALL SIZES ARE IN PLOTTER UNITS                        X-DIRECTION  Y-DIRECTION

            FRAME SIZE                                              10.000       10.000
            PICTURE SIZE                                            7.0000       7.0000
            POSITION OF LOWER LEFT HAND CORNER OF PICTURE           3.0000       2.0000
            POSITION OF START OF TITLE                              1.5000       1.0000
            POSITION OF UPPER LEFT HAND CORNER OF VARIABLE LIST    0.10000       8.0000
            POSITION OF AXIS                                        1.5000       1.5000

            SIZE OF CHARACTERS                                     0.16000
            WIDTH OF PAPER STRIP BETWEEN FRAMES                     5.0000

            MODEL AXIS ROTATION      0.000E+00    1.57      0.000E+00

            DISPLACED SHAPE OF  U       WILL BE DRAWN
            THE UNDEFORMED CONFIGURATION WILL BE DRAWN IN DOTTED LINES
```

60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING

B O U N D A R Y   C O N D I T I O N S

NODE	DOF	AMP. REF.	MAGNITUDE	NODE	DOF	AMP. REF.	MAGNITUDE
169	1		0.00000E+00	169	2		0.00000E+00
169	3		0.00000E+00	169	4		0.00000E+00
10169	2		0.00000E+00	10169	3		0.00000E+00
10169	4		0.00000E+00				

C O N C E N T R A T E D   L O A D S

NODE	DOF	AMP. REF.	AMPLITUDE	NODE	DOF	AMP. REF.	AMPLITUDE	NODE	DOF	AMP. REF.
169	6		-500.00	169	5		-500.00	10169	6	
10169	5		500.00	10169	1		-9.00000E+05			

60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING

M E S H   P L O T T I N G

```
*PLOT
*NOERASE
*DETAIL,ELSET=ANGLE,SECTION SCALING=20.
*VIEW POINT,DEFINITION=MODEL AXIS ROTATION
*DRAW
```

PLOT FRAME 1 CONSISTS OF ELSET ANGLE

ALL SIZES ARE IN PLOTTER UNITS	X-DIRECTION	Y-DIRECTION
FRAME SIZE	10.000	10.000
PICTURE SIZE	7.0000	7.0000
POSITION OF LOWER LEFT HAND CORNER OF PICTURE	3.0000	2.0000
POSITION OF START OF TITLE	1.5000	1.0000
POSITION OF UPPER LEFT HAND CORNER OF VARIABLE LIST	0.10000	8.0000
POSITION OF AXIS	1.5000	1.5000

SIZE OF CHARACTERS 0.20000
WIDTH OF PAPER STRIP BETWEEN FRAMES 5.0000

THE VIEW ANGLES ARE 0.000E+00 1.57 0.000E+00

NUMBER OF COLORS AVAILABLE 1

```
*DETAIL,ELSET=PLATE,SECTION SCALING=20.
*SHRINK,FACTOR=0.1
*VIEW POINT,DEFINITION=MODEL AXIS ROTATION
*DRAW
```

PLOT FRAME 2 CONSISTS OF ELSET PLATE

ALL SIZES ARE IN PLOTTER UNITS	X-DIRECTION	Y-DIRECTION
FRAME SIZE	10.000	10.000
PICTURE SIZE	7.0000	7.0000
POSITION OF LOWER LEFT HAND CORNER OF PICTURE	3.0000	2.0000
POSITION OF START OF TITLE	1.5000	1.0000
POSITION OF UPPER LEFT HAND CORNER OF VARIABLE LIST	0.10000	8.0000
POSITION OF AXIS	1.5000	1.5000

SIZE OF CHARACTERS 0.20000

```
  ABAQUS PRODUCTION VERSION 4-7-22                                 DATE  5MAY 90      TIME 17:26:15        PAGE   40
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

  60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
                 WIDTH OF PAPER STRIP BETWEEN FRAMES                           5.0000

                 THE VIEW ANGLES ARE      0.000E+00    1.57       0.000E+00

                 NUMBER OF COLORS AVAILABLE        1

*VIEW POINT
*SHRINK,FACTOR=0.2
*DETAIL,ELSET=ANGLE
*DRAW

PLOT FRAME     3  CONSISTS OF ELSET  ANGLE
                                                                      X-DIRECTION  Y-DIRECTION
                 ALL SIZES ARE IN PLOTTER UNITS

                 FRAME SIZE                                            10.000       10.000
                 PICTURE SIZE                                          7.0000       7.0000
                 POSITION OF LOWER LEFT HAND CORNER OF PICTURE         3.0000       2.0000
                 POSITION OF START OF TITLE                            1.5000       1.0000
                 POSITION OF UPPER LEFT HAND CORNER OF VARIABLE LIST  0.10000       8.0000
                 POSITION OF AXIS                                      1.5000       1.5000

                 SIZE OF CHARACTERS                                        0.20000
                 WIDTH OF PAPER STRIP BETWEEN FRAMES                        5.0000

                 NUMBER OF COLORS AVAILABLE        1

*DETAIL,ELSET=FIGURE
*DRAW

PLOT FRAME     4  CONSISTS OF ELSET  FIGURE
                                                                      X-DIRECTION  Y-DIRECTION
                 ALL SIZES ARE IN PLOTTER UNITS

                 FRAME SIZE                                            10.000       10.000
                 PICTURE SIZE                                          7.0000       7.0000
                 POSITION OF LOWER LEFT HAND CORNER OF PICTURE         3.0000       2.0000
                 POSITION OF START OF TITLE                            1.5000       1.0000
                 POSITION OF UPPER LEFT HAND CORNER OF VARIABLE LIST  0.10000       8.0000
                 POSITION OF AXIS                                      1.5000       1.5000

                 SIZE OF CHARACTERS                                        0.20000
                 WIDTH OF PAPER STRIP BETWEEN FRAMES                        5.0000

                 NUMBER OF COLORS AVAILABLE        1
```

```
  ABAQUS PRODUCTION VERSION 4-7-22                 DATE  5MAY 90     TIME 17:26:15        PAGE   41
 FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

  60 DEC. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING
*DETAIL,NSET=JANGLE
*PLOT MODE,DOTSIZE=0.002
*DRAW,NODENUM

PLOT FRAME    5  CONSISTS OF ALL ELEMENTS

                 ALL SIZES ARE IN PLOTTER UNITS                       X-DIRECTION  Y-DIRECTION

                 FRAME SIZE                                             10.000       10.000
                 PICTURE SIZE                                           7.0000       7.0000
                 POSITION OF LOWER LEFT HAND CORNER OF PICTURE          3.0000       2.0000
                 POSITION OF START OF TITLE                             1.5000       1.0000
                 POSITION OF UPPER LEFT HAND CORNER OF VARIABLE LIST   0.10000       8.0000
                 POSITION OF AXIS                                       1.5000       1.5000

                 SIZE OF CHARACTERS                                          0.20000
                 WIDTH OF PAPER STRIP BETWEEN FRAMES                          5.0000

                 NUMBER OF COLORS AVAILABLE      1

*SHRINK
```

```
 ABAQUS PRODUCTION VERSION 4-7-22                          DATE  5MAY 90      TIME 17:26:15        PAGE   42
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

 60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING

                         W A V E F R O N T   M I N I M I Z A T I O N

 NUMBER OF NODES          243
 NUMBER OF ELEMENTS        72
 ORIGINAL MAXIMUM D.O.F WAVEFRONT ESTIMATED AS        270
 ORIGINAL RMS D.O.F WAVEFRONT ESTIMATED AS            201

 SEARCH FOR POSSIBLE STARTING NODES IS COMPLETED

 PHERIPHERAL DIAMETER IS DEFINED BY NODES                 321    10321

 WAVEFRONT OPTIMIZED  BY CHOOSING     10321 AS THE STARTING NODE

                        P R O B L E M   S I Z E

     NUMBER OF ELEMENTS IS                                      72
     NUMBER OF NODES IS                                        243
     TOTAL NUMBER OF VARIABLES IN THE MODEL                   1458
     (DEGREES OF FREEDOM PLUS ANY LAGRANGE MULTIPLIER VARIABLES)
     MAXIMUM D.O.F. WAVEFRONT ESTIMATED AS                     132
     RMS WAVEFRONT ESTIMATED AS                                111

     FILE SIZES - THESE VALUES ARE IN WORDS AND ARE CONSERVATIVE UPPER BOUNDS

       UNIT          LENGTH

         2           127717
        19            38200
        21           113336
        22           113336
        25            12888
        26            12888
        28             3672

     IF THE RESTART FILE IS WRITTEN, ITS LENGTH WILL BE APPROXIMATELY
                    29242 WORDS WRITTEN IN THE PRE PROGRAM
          PLUS      14176 WORDS WRITTEN AT THE BEGINNING OF EACH STEP
          PLUS     136496 WORDS FOR EACH INCREMENT WRITTEN TO THE RESTART FILE
```

```
 ABAQUS PRODUCTION VERSION 4-7-22                    DATE  5MAY 90      TIME 17:26:15        PAGE   43
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

 60 DEG. 5x5x5/16" SHELL ELEMENTS-END PLATES LOAD-TORSIONAL BUCKLING

     ALLOCATED WORKSPACE                                           228948

                THIS IS A DATA CHECK RUN. ANALYSIS ENDS.
```

Appendix E
TYPICAL RESULTS OF FINITE ELEMENT ANALYSIS FOR SCHIFFLERIZED 4X4X1/4 IN. (100X100X6MM) ANGLE
PART A - OPTIONS BEING PROCESSED

```
                    A B A Q U S


           THIS PROGRAM HAS BEEN DEVELOPED BY

            HIBBITT, KARLSSON AND SORENSEN, INC.
            100 MEDWAY STREET
            PROVIDENCE, R.I. 02906


         THIS IS A PROPRIETARY PROGRAM AND IS MADE
         AVAILABLE FOR INTERNAL USE AT UNIVERSITY OF WINDSOR,
         UNDER THE TERMS OF THE ACADEMIC LICENSE AGREEMENT
         WITH H.K.S.  ALL USAGE MUST BE UNDER THE DIRECT
         SUPERVISION AND CONTROL OF THE DESIGNATED USER.
         THE DESIGNATED USER IS DR. GEORGE ABDEL-SAYED.
         ANY NON-ACADEMIC USAGE OF THE PROGRAM REQUIRES
         PAYMENT OF A MONTHLY CHARGE.  ASSISTANCE AND
         OTHER INFORMATION MAY BE OBTAINED FROM THE
         DESIGNATED USER.

          FOR ASSISTANCE OR ANY OTHER INFORMATION CALL
                        401-861-0820

      * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      *                  ****************                        *
      *                  *  N O T I C E *                        *
      *                  ****************                        *
      *                                                          *
      *            THIS IS ABAQUS VERSION 4-7.                   *
      *                                                          *
      * SOME INPUT DATA OPTIONS AND USER SUBROUTINE INTERFACES   *
      *         ARE INCOMPATIBLE WITH VERSION 4-5.               *
      *                                                          *
      *        PLEASE MAKE SURE YOU ARE USING VERSION            *
      *              4-6 OR 4-7 MANUALS.                         *
      * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
```

```
ABAQUS PRODUCTION VERSION 4-7-22                                   DATE  5MAY 90      TIME  9:42:56        PAGE   2
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

*PRINT,ECHO=YES,MODEL=NO,HISTORY=NO
```

```
  ABAQUS PRODUCTION VERSION 4-7-22                          DATE   5MAY 90      TIME  0:42:50       PAGE   1
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

                              A B A Q U S   I N P U T   E C H O

        5    10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
-----------------------------------------------------------------------------------------
*HEADING
60 DLG. 4X4X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING
**DATACHECK
*PREPRINT,ECHO=YES,MODEL=NO,HISTORY=NO
*NODE
           1 ,0.000000000E+00 , 3.21679401     , -2.11871719
           3 ,0.000000000E+00 ,0.619718565     ,-0.618718565
           5 ,0.000000000E+00 ,0.000000000E+00, 0.000000000E+00
           7 ,0.000000000E+00 ,0.619718565     , 0.618718565
           9 ,0.000000000E+00 , 3.21679401     , 2.11871719
          23 ,0.000000000E+00 , 1.55456924     , 0.000000000E+00
**          31 ,0.000000000E+00 , 2.09407864     , -1.34143353
          31 ,0.000000000E+00 , 3.99407864     , -1.34143353
**          41 ,0.000000000E+00 , 2.09407864     , 1.34143353
          41 ,0.000000000E+00 , 3.99407864     , 1.34143353
          53 ,0.000000000E+00 , 5.33551311     , 0.000000000E+00
*NGEN,NSET=BOT
1,3,1
3,5,1
5,7
7,9
3,23,10
23,41,9
1,31,15
31,53,11
9,41,16
41,53,6
7,23,8
23,31,4
8,32,12
1,23,11
5,23,9
*NCOPY,CHANGE NUMBER=1000,OLDSET=BOT,SHIFT,NEW SET=TOP
65.125
0,0
*NSET,NSET=END1,GENERATE
1,9
*NSET,NSET=END2,GENERATE
1001,1009
*NFILL,NSET=JANGLE
-----------------------------------------------------------------------------------------
        5    10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
```

ABAQUS PRODUCTION VERSION 4-7-22 DATE 5MAY 90 TIME 9:42:56 PAGE 4
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

```
         5    10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
     ---------------------------------------------------------------------------------
     END1,END2,10,100
     *ELEMENT,TYPE=S4R
     101,1,101,102,2
     *ELGEN,ELSET=ANGLE
     101,10,100,100,8,1,1
     *ELSET,ELSET=E1,GENERATE
     101,1001
     102,1002
     *ELSET,ELSET=E2,GENERATE
     103,1003
     104,1004
     *ELSET,ELSET=E3,GENERATE
     105,1005
     106,1006
     *ELSET,ELSET=E4,GENERATE
     107,1007
     108,1008
     *ELEMENT,TYPE=S4R,ELSET=PLATE
     1,1,2,12,16
     2,2,3,13,12
     3,3,4,14,13
     4,4,5,6,14
     5,13,14,15,23
     6,14,6,7,15
     7,15,7,8,20
     8,20,8,9,25
     ***ELEMENT,TYPE=S8R,ELSET=PLATE
     **1,1,3,23,31,2,13,27,16
     **2,3,5,7,23,4,6,15,13
     **3,31,23,41,53,27,32,47,42
     **4,23,7,9,41,15,8,25,32
     *ELCOPY,ELEMENT SHIFT=10,OLD SET=PLATE,NEW SET=PLATE,SHIFT NODES=1000
     *ELSET,ELSET=EALL
     ANGLE,PLATE
     *MATERIAL,NAME=M1
     *ELASTIC
     29.000e6,0.3000
     **PLASTIC
     **44.13,0,0
     *MATERIAL,NAME=M2
     *ELASTIC
     29.000e6,0.3000
     *BOUNDARY
     23,1,4
     ---------------------------------------------------------------------------------
         5    10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
```

```
1023,2,4
*SHELL SECTION,ELSET=ANGLE,MATERIAL=M1
0.2500
*SHELL SECTION,ELSET=PLATE,MATERIAL=M2
0.75
**
*PLOT
60 DEG. 3X3X3/8"  SHELL ELEMENTS-END PLATES LOAD-FLEXURAL BUCKLING
0
0.16, , , , , ,0.05
*NDERASE
*DETAIL,ELSET=ANGLE,SECTION SCALING=20.
*VIEW POINT,DEFINITION=MODEL AXIS ROTATION
0.0,90.0
*DRAW
*DETAIL,ELSET=PLATE,SECTION SCALING=20.
*SHRINK,FACTOR=0.1
*VIEW POINT,DEFINITION=MODEL AXIS ROTATION
0.0,90.0
*DRAW
*ERASE
*VIEW POINT
0.5,1.0,0.5
*SHRINK,FACTOR=0.2
*DETAIL,ELSET=ANGLE
*DRAW,ELNUM
*DETAIL,NSET=JANGLE
*PLOT MODE,DOTSIZE=0.002
*DRAW,NODENUM
*SHRINK
*STEP,NLGEOM
*STATIC,PTOL=10.,MTOL=10.
*NODE PRINT,FREQ=0
**U
**RF
*ELPRINT,FREQ=0
*CLOAD
505,2,200.0
*DETAIL,ELSET=ANGLE
*VIEW POINT,DEFINITION=MODEL AXIS ROTATION
45.0
*DISPLACED
U
*END STEP
```

```
ABAQUS PRODUCTION VERSION 4-7-22                                    DATE  5MAY 90      TIME  0:42:56        PAGE
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

                   5    10    15    20    25    30    35    40    45    50    55    60    65    70    75    80
                ---------------------------------------------------------------------------------------------
                **RESTART,WRITE,FREQ=50
 CARD  130      *STEP,NLGEOM,INC=500
                *STATIC,PTOL=10.0,MTOL=10.0
                0.1,1.0,0.001,0.1
                *ELPRINT,FREQ=0
                **S
 CARD  135      **E
                **SF
                **CE,CEEQ
                *NODE PRINT,FREQ=1
                **U
 CARD  140      RF
                *ELFILE,FREQ=0
                **SF
                **CF
                *NODE FILE,FREQ=0
 CARD  145      **U
                *PRINT,RESIDUAL=NO
                ***DLOAD
                **ETOP,BX,-15.000E3
                *CLOAD
 CARD  150      1023,1,-200.0E3
                *PLOT,FREQ=4
                *PLOTMODE,DOTSIZE=0.065
                *SHRINK,FACTOR=0.0
                *ZOOM,FACTOR=1.5
 CARD  155      *DETAIL,ELSET=E1
                *CENTER
                30.0,0.0,0.0
                *VIEW POINT,DEFINITION=MODEL AXIS ROTATION
                -15.0
 CARD  160      *NOCPAS
                *CONTOUR
                S11,0
                *DETAIL,ELSET=E2
                *CENTER
 CARD  165      30.0,0.0,0.0
                *VIEW POINT,DEFINITION=MODEL AXIS ROTATION
                0.
                *CONTOUR
                S11,0
 CARD  170      *DETAIL,ELSET=E3
                *CENTER
                30.0,0.0,0.0
                ---------------------------------------------------------------------------------------------
                   5    10    15    20    25    30    35    40    45    50    55    60    65    70    75    80
```

```
ABAQUS PRODUCTION VERSION 4-7-22                          DATE  5MAY 90      TIME  0:42:56        PAGE     7
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

        5    10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
   ---------------------------------------------------------------------------------
   *VIEW POINT,DEFINITION=MODEL AXIS ROTATION
   90.0
   *CONTOUR
   S11,8
   *DETAIL,ELSET=E4
   *CENTER
   35.0,0.0,0.0
   *VIEW POINT,DEFINITION=MODEL AXIS ROTATION
   105.0
   *CONTOUR
   S11,0
   *ERASE
   *DETAIL,ELSET=ANGLE
   *ZOOM,FACTOR=1.0
   *VIEWPOINT,DEFINITION=MODEL AXIS ROTATION
   -45.0
   *DISPLACED
   U
   *DETAIL,ELSET=ANGLE
   *ZOOM,FACTOR=1.0
   *VIEWPOINT,DEFINITION=MODEL AXIS ROTATION
   45.0
   *DISPLACED
   U
   *DETAIL,ELSET=ANGLE
   *ZOOM,FACTOR=1.0
   *VIEWPOINT,DEFINITION=MODEL AXIS ROTATION
   0.0,90.0
   *DISPLACED
   U
   *END STEP
   ---------------------------------------------------------------------------------
        5    10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
   ---------------------------------------------------------------------------------
```

```
ABAQUS PRODUCTION VERSION 4-7-22                     DATE  5MAY 90      TIME  0:42:56        PAG
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.


 OPTIONS BEING PROCESSED
****************************

*HEADING
 60 DEG. 4X4X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING
*NODE
*NGEN,NSET=BOT
*NCOPY,CHANGE NUMBER=1000,OLDSET=BOT,SHIFT,NEW SET=TOP
*NSET,NSET=END1,GENERATE
*NSET,NSET=END2,GENERATE
*NFILL,NSET=JANGLE
  THE FOLLOWING NODES WILL BE USED IN THE NFILL GENERATION

      BOUND  1           1     2     3     4     5     6     7     8     9

      BOUND  2        1001  1002  1003  1004  1005  1006  1007  1008  1009
*ELEMENT,TYPE=S4R
*ELGEN,ELSET=ANGLE
*ELSET,ELSET=E1,GENERATE
*ELSET,ELSET=E2,GENERATE
*ELSET,ELSET=E3,GENERATE
*ELSET,ELSET=E4,GENERATE
*ELEMENT,TYPE=S4R,ELSET=PLATE
*ELCOPY,ELEMENT SHIFT=10,OLD SET=PLATE,NEW SET=PLATE,SHIFT NODES=1000
*ELSET,ELSET=EALL
*MATERIAL,NAME=M1
*ELASTIC
*MATERIAL,NAME=M2
*ELASTIC
*SHELL SECTION,ELSET=ANGLE,MATERIAL=M1
*SHELL SECTION,ELSET=PLATE,MATERIAL=M2
*STEP,NLGEOM
*STATIC,PTOL=10.,MTOL=10.
*ELPRINT,FREQ=0
*DETAIL,ELSET=ANGLE
*VIEW POINT,DEFINITION=MODEL AXIS ROTATION
*DISPLACED
*END STEP
*STEP,NLGEOM,INC=500
*STATIC,PTOL=10.0,MTOL=10.0
*ELPRINT,FREQ=0
*ELFILE,FREQ=0
```

```
   ABAQUS PRODUCTION VERSION 4-7-22                              DATE  5MAY 90      TIME  0:42:56        PAGE    9
 FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

    60 DEG. 4X4X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING
*PRINT,RESIDUAL=NO
*PLOT,FREQ=4
*PLOTMODE,DOTSIZE=0.005
*SHRINK,FACTOR=0.0
*ZOOM,FACTOR=1.5
*DETAIL,ELSET=E1
*CENTER
*VIEW POINT,DEFINITION=MODEL AXIS ROTATION
*NOERASE
*CONTOUR
*DETAIL,ELSET=E2
*CENTER
*VIEW POINT,DEFINITION=MODEL AXIS ROTATION
*CONTOUR
*DETAIL,ELSET=E3
*CENTER
*VIEW POINT,DEFINITION=MODEL AXIS ROTATION
*CONTOUR
*DETAIL,ELSET=E4
*CENTER
*VIEW POINT,DEFINITION=MODEL AXIS ROTATION
*CONTOUR
*ERASE
*DETAIL,ELSET=ANGLE
*ZOOM,FACTOR=1.0
*VIEWPOINT,DEFINITION=MODEL AXIS ROTATION
*DISPLACED
*DETAIL,ELSET=ANGLE
*ZOOM,FACTOR=1.0
*VIEWPOINT,DEFINITION=MODEL AXIS ROTATION
*DISPLACED
*DETAIL,ELSET=ANGLE
*ZOOM,FACTOR=1.0
*VIEWPOINT,DEFINITION=MODEL AXIS ROTATION
*DISPLACED
*END STEP
*BOUNDARY
*STEP,NLGEOM
*STATIC,PTOL=10.,MTOL=10.
*NODE PRINT,FREQ=0
*CLOAD
*STEP,NLGEOM,INC=500
*STATIC,PTOL=10.0,MTOL=10.0
*NODE PRINT,FREQ=1
*NODE FILE,FREQ=0
*CLOAD
```

```
ABAQUS PRODUCTION VERSION 4-7-22                              DATE  5MAY 90      TIME  9:42:56        PAGE  1
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

 60 DEG. 4X4X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING

                     M E S H   P L O T T I N G

*PLOT
*NOERASE
*DETAIL,ELSET=ANGLE,SECTION SCALING=20.
*VIEW POINT,DEFINITION=MODEL AXIS ROTATION
*DRAW

PLOT FRAME     1  CONSISTS OF ELSET  ANGLE

                  ALL SIZES ARE IN PLOTTER UNITS                               X-DIRECTION  Y-DIRECTION

                  FRAME SIZE                                                     10.000       10.000
                  PICTURE SIZE                                                   7.0000       7.0000
                  POSITION OF LOWER LEFT HAND CORNER OF PICTURE                  3.0000       2.0000
                  POSITION OF START OF TITLE                                     1.5000       1.0000
                  POSITION OF UPPER LEFT HAND CORNER OF VARIABLE LIST            0.10000      8.0000
                  POSITION OF AXIS                                               1.5000       1.5000

                  SIZE OF CHARACTERS                                                  0.16000
                  WIDTH OF PAPER STRIP BETWEEN FRAMES                                 5.0000

                  THE VIEW ANGLES ARE      0.000E+00     1.57        0.000E+00

                  NUMBER OF COLORS AVAILABLE        1

*DETAIL,ELSET=PLATE,SECTION SCALING=20.
*SHRINK,FACTOR=0.1
*VIEW POINT,DEFINITION=MODEL AXIS ROTATION
*DRAW

PLOT FRAME     2  CONSISTS OF ELSET  PLATE

                  ALL SIZES ARE IN PLOTTER UNITS                               X-DIRECTION  Y-DIRECTION

                  FRAME SIZE                                                     10.000       10.000
                  PICTURE SIZE                                                   7.0000       7.0000
                  POSITION OF LOWER LEFT HAND CORNER OF PICTURE                  3.0000       2.0000
                  POSITION OF START OF TITLE                                     1.5000       1.0000
                  POSITION OF UPPER LEFT HAND CORNER OF VARIABLE LIST            0.10000      9.0000
                  POSITION OF AXIS                                               1.5000       1.5000

                  SIZE OF CHARACTERS                                                  0.16000
```

```
ABAQUS PRODUCTION VERSION 4-7-22                     DATE  5MAY 90       TIME  3:42:56        PAGE   11
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

 60 DEG. 4X4X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING
              WIDTH OF PAPER STRIP BETWEEN FRAMES                                 5.0000

              THE VIEW ANGLES ARE      0.000E+00    1.57       0.000E+00

              NUMBER OF COLORS AVAILABLE       1

*VIEW POINT
*SHRINK,FACTOR=0.2
*DETAIL,ELSET=ANGLE
*DRAW,ELNUM

PLOT FRAME     3  CONSISTS OF ELSET  ANGLE

              ALL SIZES ARE IN PLOTTER UNITS                          X-DIRECTION  Y-DIRECTION

              FRAME SIZE                                                10.000      10.000
              PICTURE SIZE                                              7.0000      7.0000
              POSITION OF LOWER LEFT HAND CORNER OF PICTURE             3.0000      2.0000
              POSITION OF START OF TITLE                                1.5000      1.0000
              POSITION OF UPPER LEFT HAND CORNER OF VARIABLE LIST      0.10000      8.0000
              POSITION OF AXIS                                          1.5000      1.5000

              SIZE OF CHARACTERS                                           0.16000
              WIDTH OF PAPER STRIP BETWEEN FRAMES                          5.0000

              NUMBER OF COLORS AVAILABLE       1

*DETAIL,ELSET=ANGLE
*PLOT MODE,DOTSIZE=0.002
*DRAW,NODENUM

PLOT FRAME     4  CONSISTS OF ALL ELEMENTS

              ALL SIZES ARE IN PLOTTER UNITS                          X-DIRECTION  Y-DIRECTION

              FRAME SIZE                                                10.000      10.000
              PICTURE SIZE                                              7.0000      7.0000
              POSITION OF LOWER LEFT HAND CORNER OF PICTURE             3.0000      2.0000
              POSITION OF START OF TITLE                                1.5000      1.0000
              POSITION OF UPPER LEFT HAND CORNER OF VARIABLE LIST      0.10000      8.0000
              POSITION OF AXIS                                          1.5000      1.5000

              SIZE OF CHARACTERS                                           0.16000
              WIDTH OF PAPER STRIP BETWEEN FRAMES                          5.0000

              NUMBER OF COLORS AVAILABLE       1
```

```
                                                DATE  5MAY 90      TIME  0:42:56        PAGE    12
  ABAQUS PRODUCTION VERSION 4-7-22
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

  60 DEG. 4X4X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING
*SHRINK
```

```
JOB COMPLETED AT 01:06:38 FOR USER: KLB        DIST: ADLURI

ABAQUS PRODUCTION VERSION 4-7-22                          DATE  5MAY 90      TIME  0:42:56          PAGE    13
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

 60 DEG. 4X4X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING

                    W A V E F R O N T   M I N I M I Z A T I O N

 NUMBER OF NODES              115
 NUMBER OF ELEMENTS            96
 ORIGINAL MAXIMUM D.O.F WAVEFRONT ESTIMATED AS      120
 ORIGINAL RMS D.O.F WAVEFRONT ESTIMATED AS          109

 SEARCH FOR POSSIBLE STARTING NODES IS COMPLETED

 PHERIPHERAL DIAMETER IS DEFINED BY NODES                 23     1023

 WAVEFRONT OPTIMIZED BY CHOOSING        1023 AS THE STARTING NODE

                          P R O B L E M   S I Z E

      NUMBER OF ELEMENTS IS                                       96
      NUMBER OF NODES IS                                         115
      TOTAL NUMBER OF VARIABLES IN THE MODEL                     690
      (DEGREES OF FREEDOM PLUS ANY LAGRANGE MULTIPLIER VARIABLES)
      MAXIMUM D.O.F. WAVEFRONT ESTIMATED AS                      100
      RMS WAVEFRONT ESTIMATED AS                                  06

    FILE SIZES - THESE VALUES ARE IN WORDS AND ARE CONSERVATIVE UPPER BOUNDS

      UNIT          LENGTH

        2            18379
       21            21600
       22            21600
       25             5760
       26             5760
       20             2592

    IF THE RESTART FILE IS WRITTEN, ITS LENGTH WILL BE APPROXIMATELY
                    14080 WORDS WRITTEN IN THE PRE PROGRAM
        PLUS         6336 WORDS WRITTEN AT THE BEGINNING OF EACH STEP
        PLUS        29110 WORDS FOR EACH INCREMENT WRITTEN TO THE RESTART FILE
```

```
ABAQUS PRODUCTION VERSION 4-7-22          DATE  5MAY 90     TIME  0:42:56       PAGE   14
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

60 DEG. 4X4X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING

    ALLOCATED WORKSPACE                                          160034
```

Appendix F

TYPICAL RESULTS OF FINITE ELEMENT ANALYSIS FOR SCHIFFLERIZED 4X4X1/4 IN. (100X100X6MM) ANGLE PART B - NONLINEAR ANALYSIS

```
ABAQUS PRODUCTION VERSION 4-7-22                    DATE  5MAY 90      TIME  0:43:45        PAGE      1
FOR USE AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

65 DEG. 4X4X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING                          STEP    1  INCREM
                                                                                    TIME COMPLETED IN THIS

                    S T E P    1

                              S T A T I C   A N A L Y S I S

                      AUTOMATIC CONTROL WITH -
                      A SUGGESTED INITIAL TIME INCREMENT OF             1.00
                      AND A TOTAL TIME PERIOD OF                        1.00
                      THE MINIMUM TIME INCREMENT ALLOWED IS           1.000E-05
                      THE MAXIMUM TIME INCREMENT ALLOWED IS             1.00

                      EQUILIBRIUM TOLERANCES -
                      TOLERANCE ON INDIVIDUAL FORCE COMPONENTS                 10.0
                      TOLERANCE ON INDIVIDUAL MOMENT COMPONENTS                10.0

                      LARGE DISPLACEMENT THEORY WILL BE USED

                      MAXIMUM NUMBER OF INCREMENTS ALLOWED IN THIS STEP IS     10
                      MAXIMUM NUMBER OF ITERATIONS ALLOWED PER INCREMENT IS     6

                      PRINT OF INCREMENT NUMBER, TIME, ETC., EVERY    1  INCREMENTS


                      INCREMENT NUMBER     1  ATTEMPT NUMBER     1


                      TIME INCREMENT =     1.00
```

ABAQUS PRODUCTION VERSION 4-7-22 DATE 5MAY 90 TIME 0:43:45 PAGE 2
AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

4X4X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING

STEP 1 INCREMENT
TIME COMPLETED IN THIS STEP

ITERATION 1 NO CONVERGENCE

MAXIMUM RESIDUALS ASSOCIATED WITH EACH D.O.F.

D.O.F.	MAXIMUM RESIDUAL	OCCURS AT NODE
1	9.80	8
2	43.8	105
3	-13.6	909
4	-6.53	108
5	-0.216	309
6	0.148	305

MAXIMUM DISPLACEMENT INCREMENT ASSOCIATED WITH

D.O.F.	MAXIMUM DISPLACEMENT INCREMENT	OCCURS AT NODE
1	2.447E-03	1025
2	2.569E-02	555
3	1.087E-04	16
4	-8.456E-05	1029
5	2.125E-05	20
6	1.222E-03	5

ITERATION 2 CONVERGENT SOLUTION

MAXIMUM RESIDUALS ASSOCIATED WITH EACH D.O.F.

D.O.F.	MAXIMUM RESIDUAL	OCCURS AT NODE
1	1.340E-03	1014
2	2.199E-02	906
3	-2.057E-02	914
4	5.051E-02	904
5	-2.049E-02	202
6	1.166E-02	202

MAXIMUM DISPLACEMENT INCREMENT ASSOCIATED WITH

D.O.F.	MAXIMUM DISPLACEMENT INCREMENT	OCCURS AT NODE
1	2.424E-03	1025
2	2.549E-02	565
3	1.093E-04	16
4	-8.478E-05	20
5	2.163E-05	20
6	1.222E-03	5

TIME COMPLETED DURING THIS STEP 1.00 , TIME INCREMENT COMPLETED 1.00 , FRACTION OF STEP COMPLETED 1.
TOTAL ACCUMULATED TIME 1.00

STARTING FRAME 1

FRAME 1 SHOWS DISPLACED POSITION BASED ON U WITH MAGNIFICATION FACTOR OF 174.

```
ABAQUS PRODUCTION VERSION 4-7-22                                DATE  9MAY 90     TIME  0:43:45        PAGE    1
AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM H S, INC.
                                                                                    STEP    2  INCREMENT    1
G. 4X4X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING                      TIME COMPLETED IN THIS STEP

          S T E P    2

                   S T A T I C   A N A L Y S I S

            AUTOMATIC CONTROL WITH -
            A SUGGESTED INITIAL TIME INCREMENT OF              1.000E-01
            AND A TOTAL TIME PERIOD OF                          1.00
            THE MINIMUM TIME INCREMENT ALLOWED IS              1.000E-03
            THE MAXIMUM TIME INCREMENT ALLOWED IS              1.000E-01

            EQUILIBRIUM TOLERANCES -
            TOLERANCE ON INDIVIDUAL FORCE COMPONENTS                10.0
            TOLERANCE ON INDIVIDUAL MOMENT COMPONENTS               10.0

            LARGE DISPLACEMENT THEORY WILL BE USED

            MAXIMUM NUMBER OF INCREMENTS ALLOWED IN THIS STEP IS   500
            MAXIMUM NUMBER OF ITERATIONS ALLOWED PER INCREMENT IS    6

            PRINT OF RESIDUALS DURING ITERATION SUPPRESSED

            PRINT OF INCREMENT NUMBER, TIME, ETC., EVERY    1  INCREMENTS


            INCREMENT NUMBER     1  ATTEMPT NUMBER     1

            TIME INCREMENT =    1.000E-01
```

```
A. PRODUCTION VERSION 4-7-22                              DATE  5MAY 90       TIME  0:43:45          PAGE    4
  AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

 4X4X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING
                                                                                    STEP     2  INCREMENT
                                                                                  TIME COMPLETED IN THIS STEP

       ITERATION  2  CONVERGENT SOLUTION

 COMPLETED DURING THIS STEP  1.000E-01,  TIME INCREMENT COMPLETED  1.000E-01,  FRACTION OF STEP COMPLETED  1.
 ACCUMULATED TIME             1.10


                          N O D E   O U T P U T


 FOLLOWING TABLE IS PRINTED FOR ALL NODES

 FOOT-    RF1          RF2          RF3          RM1          RM2          RM3
 NOTE

       2.0000E+04   -99.05       1.2907E-02   4.7797E-03   0.0000E+00   0.0000E+00
       0.0000E+00   -99.05       1.2910E-02   4.7797E-03   0.0000E+00   0.0000E+00

       2.0000E+04   0.0000E+00   1.2910E-02   4.7797E-03   0.0000E+00   0.0000E+00
           23           1          1023          23           1            1

       0.0000E+00   -99.05       0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00
            1          1023          1            1           1            1


                    INCREMENT NUMBER     2  ATTEMPT NUMBER    1


                    TIME INCREMENT =    1.000E-01
```

```
U. PRODUCTION VERSION 4-7-22                              DATE  5MAY 90      TIME  0:43:45          PAGE    5
  AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.
                                                                                              STEP     2  INCREMENT
.. 4X4X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING                                TIME COMPLETED IN THIS STEP  1

     ITERATION  3  CONVERGENT SOLUTION

 COMPLETED DURING THIS STEP  C.200    ,  TIME INCREMENT COMPLETED  1.000E-01,  FRACTION OF STEP COMPLETED  ..
 ACCUMULATED TIME             1.20


                              N O D E   O U T P U T


LLOWING TABLE IS PRINTED FOR ALL NODES

 NOT-   RF1          RF2          RF3          RM1          RM2          RM3
 NOTE

        4.0000E+04   -99.97       4.1832E-02  -5.2571E-03   0.0000E+00   0.0000E+00
        0.0000E+00   -99.97       4.1822E-02  -5.2565E-03   0.0000E+00   0.0000E+00

        4.0000E+04   0.0000E+00   4.1932E-02   0.0000E+00   0.0000E+00   0.0000E+00
           23           1            23            1            1            1

        0.0000E+00   -99.97       0.0000E+03  -5.2571E-03   0.0000E+00   0.0000E+00
           1          1023           1            23            1            1


                  INCREMENT NUMBER    3  ATTEMPT NUMBER    1

                  TIME INCREMENT =    1.000E-01
```

```
ABAQUS VERSION 4-7-22                                DATE  5MAY 90      TIME  ::43:45        PAGE    6
UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.
                                                                                STEP    2  INCREMENT    3
W6X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING                      TIME COMPLETED IN THIS STEP  .

  ITERATION  4  CONVERGENT SOLUTION

TIME USED DURING THIS STEP  0.300   ,  TIME INCREMENT COMPLETED  1.000E-01,  FRACTION OF STEP COMPLETED  0.300
ACCUMULATED TIME              1.30


                     N O D E   O U T P U T


  TABLE IS PRINTED FOR ALL NODES

    RF1           RF2          RF3           RM1           RM2           RM3

  6.0000E+04   -100.0      -5.4965E-03   8.2399E-02   0.0000E+00   0.0000E+00
  0.0000E+00   -100.0      -5.4995E-03   8.2399E-02   0.0000E+00   0.0000E+00
  6.0000E+04   0.0000E+00   0.0000E+00   8.2399E-02   0.0000E+00   0.0000E+00
      23           1            1          1023           1            1
  0.0000E+00   -100.0      -5.4995E-03   0.0000E+00   0.0000E+00   0.0000E+00
      1           23          1023           1            1            1


            INCREMENT NUMBER    4   ATTEMPT NUMBER    1

            TIME INCREMENT =    1.000E-01
```

```
PRODUCTION VERSION 4-7-22                     DATE  5MAY 90     TIME  0:43:45          PAGE      7
AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.
                                                                               STEP     2  INCREMENT
..  4X4X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING                     TIME COMPLETED IN THIS STEP

THE  SYSTEM MATRIX HAS       1  NEGATIVE EIGENVALUES.

EIGENVALUE EXTRACTION STEP THE NUMBER OF NEGATIVE EIGENVALUES IS EQUAL TO THE NUMBER
EIGENVALUES BELOW THE CURRENT SHIFT POINT.
MAY BE USED TO CHECK THAT EIGENVALUES HAVE NOT BEEN MISSED.

IN CASES, NEGATIVE EIGENVALUES MEAN THAT THE SYSTEM MATRIX IS NOT POSITIVE DEFINITE:
EXAMPLE, A BIFURCATION (BUCKLING) LOAD MAY HAVE BEEN EXCEEDED.

THE  SYSTEM MATRIX HAS       1  NEGATIVE EIGENVALUES. EXPLANATIONS ARE SUGGESTED AFTER THE FIRST OCCURRENCE OF TH
THE  SYSTEM MATRIX HAS       1  NEGATIVE EIGENVALUES. EXPLANATIONS ARE SUGGESTED AFTER THE FIRST OCCURRENCE OF TH

        CONVERGENCE JUDGED UNLIKELY - INCREMENT WILL BE ATTEMPTED AGAIN WITH A SMALLER TIME INCREM


        INCREMENT NUMBER     4  ATTEMPT NUMBER     2


        TIME INCREMENT =     5.000E-02
THE  SYSTEM MATRIX HAS       1  NEGATIVE EIGENVALUES. EXPLANATIONS ARE SUGGESTED AFTER THE FIRST OCCURRENCE OF TH
THE  SYSTEM MATRIX HAS       1  NEGATIVE EIGENVALUES. EXPLANATIONS ARE SUGGESTED AFTER THE FIRST OCCURRENCE OF TH
THE  SYSTEM MATRIX HAS       1  NEGATIVE EIGENVALUES. EXPLANATIONS ARE SUGGESTED AFTER THE FIRST OCCURRENCE OF TH

        CONVERGENCE JUDGED UNLIKELY - INCREMENT WILL BE ATTEMPTED AGAIN WITH A SMALL   TIME INC


        INCREMENT NUMBER     4  ATTEMPT NUMBER     3


        TIME INCREMENT =     2.500E-02
```

```
 ... PRODUCTION VERSION 4-7-22                          DATE  5MAY 90      TIME  9:43:45        PAGE   8
 ... AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.

 DEG. 4X4X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING                          STEP    2  INCREMENT
                                                                                  TIME COMPLETED IN THIS STEP

        ITERATION  3  CONVERGENT SOLUTION

 ... COMPLETED DURING THIS STEP  0.325    ,  TIME INCREMENT COMPLETED  2.500E-02,  FRACTION OF STEP COMPLETED  .
 ...AL ACCUMULATED TIME          1.32
```

N O D E   O U T P U T

...LLOWING TABLE IS PRINTED FOR ALL NODES

FOOT-NOTE	RF1	RF2	RF3	RM1	RM2	RM3
...	6.5000E+04	-99.98	0.1625	2.988	0.0000E+00	0.0000E+00
...	0.0000E+00	-99.98	0.1625	2.988	0.0000E+00	0.0000E+00
...	6.5000E+04 23	0.0000E+00 1	0.1625 1023	2.988 23	0.0000E+00 1	0.0000E+00 1
...	0.0000E+00 1	-99.98 1023	0.0000E+00 1	0.0000E+00 1	0.0000E+00 1	0.0000E+00 1

STARTING FRAME   1

FRAME 1 CONTOUR LEVELS

I.D.	VALUE
1	-8.0000E+04
2	-6.7143E+04
3	-5.4286E+04
4	-4.1429E+04
5	-2.8571E+04
6	-1.5714E+04
7	-2857.
8	1.0000E+04

U.G. 4X4X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING

STEP 2 INCREMENT
TIME COMPLETED IN THIS STEP

STARTING FRAME 2

FRAME 2 CONTOUR LEVELS

I.D.	VALUE
1	-7.0000E+04
2	-5.8571E+04
3	-4.7143E+04
4	-3.5714E+04
5	-2.4286E+04
6	-1.2857E+04
7	-1429.
8	1.0000E+04

STARTING FRAME 3

FRAME 3 CONTOUR LEVELS

I.D.	VALUE
1	-7.0000E+04
2	-5.8571E+04
3	-4.7143E+04
4	-3.5714E+04
5	-2.4286E+04
6	-1.2857E+04
7	-1429.
8	1.0000E+04

STARTING FRAME 4

```
ABAQUS PRODUCTION VERSION 4-7-22                                       DATE  5MAY 90      TIME  0:43:45        PAGE   1
  AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.
 4X4X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING
                                                                                                   STEP    2  INCREMENT
                                                                                            TIME COMPLETED IN THIS STEP

           FRAME   4   CONTOUR LEVELS
                       I.D.       VALUE

                        1       -8.0000E+04
                        2       -6.7143E+04
                        3       -5.4286E+04
                        4       -4.1429E+04
                        5       -2.8571E+04
                        6       -1.5714E+04
                        7        -2857.
                        8        1.0000E+04

                       STARTING FRAME     5

           FRAME   5     SHOWS DISPLACED POSITION BASED ON U         WITH MAGNIFICATION FACTOR OF   21.3

                       STARTING FRAME     6

           FRAME   6     SHOWS DISPLACED POSITION BASED ON U         WITH MAGNIFICATION FACTOR OF   21.3

                       STARTING FRAME     7

           FRAME   7     SHOWS DISPLACED POSITION BASED ON U         WITH MAGNIFICATION FACTOR OF   2.40


                       INCREMENT NUMBER     5  ATTEMPT NUMBER     1

                       TIME INCREMENT =    2.500E-02
 THE SYSTEM MATRIX HAS       1     GATIVE EIGENVALUES. EXPLANATIONS ARE SUGGESTED AFTER THE FIRST OCCURRENCE OF :
```

```
UF PRODUCTION VERSION 4-7-22                          DATE  5MAY 90      TIME  0:43:45       PAGE   11
  AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.
..6. 4X4X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING
                                                                                   STEP    2  INCREMENT
                                                                          TIME COMPLETED IN THIS STEP

                   CONVERGENCE JUDGED UNLIKELY - INCREMENT WILL BE ATTEMPTED AGAIN WITH A SMALLER TIME INCR

                   INCREMENT NUMBER     5  ATTEMPT NUMBER     2

                   TIME INCREMENT =    6.250E-03
THE SYSTEM MATRIX HAS       1  NEGATIVE EIGENVALUES. EXPLANATIONS ARE SUGGESTED AFTER THE FIRST OCCURRENCE OF TH

                   CONVERGENCE JUDGED UNLIKELY - INCREMENT WILL BE ATTEMPTED AGAIN WITH A SMALLER TIME INCR

                   INCREMENT NUMBER     5  ATTEMPT NUMBER     3

                   TIME INCREMENT =    3.807E-03
THE SYSTEM MATRIX HAS       1  NEGATIVE EIGENVALUES. EXPLANATIONS ARE SUGGESTED AFTER THE FIRST OCCURRENCE OF TH

                   CONVERGENCE JUDGED UNLIKELY - INCREMENT WILL BE ATTEMPTED AGAIN WITH A SMALLER TIME INCR

                   INCREMENT NUMBER     5  ATTEMPT NUMBER     4

                   TIME INCREMENT =    2.765E-03
THE SYSTEM MATRIX HAS       1  NEGATIVE EIGENVALUES. EXPLANATIONS ARE SUGGESTED AFTER THE FIRST OCCURRENCE OF TH
```

```
  PRODUCTION VERSION 4-7-22                              DATE  5MAY 90      TIME  0:43:45        PAGE   12
  AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.
                                                                                          STEP    2  INCREMENT
  .. 4X4X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING                        TIME COMPLETED IN THIS STEP

                    CONVERGENCE JUDGED UNLIKELY - INCREMENT WILL BE ATTEMPTED AGAIN WITH A SMALLER TIME INCR

                    INCREMENT NUMBER     5  ATTEMPT NUMBER     5

                    TIME INCREMENT =    1.392E-03
  THE SYSTEM MATRIX HAS       1  NEGATIVE EIGENVALUES. EXPLANATIONS ARE SUGGESTED AFTER THE FIRST OCCURRENCE OF TH

                    CONVERGENCE JUDGED UNLIKELY - INCREMENT WILL BE ATTEMPTED AGAIN WITH A SMALLER TIME INCR

                    INCREMENT NUMBER     5  ATTEMPT NUMBER     6

                    TIME INCREMENT =    1.000E-03
  THE SYSTEM MATRIX HAS       1  NEGATIVE EIGENVALUES. EXPLANATIONS ARE SUGGESTED AFTER THE FIRST OCCURRENCE OF TH
  THE SYSTEM MATRIX HAS       1  NEGATIVE EIGENVALUES. EXPLANATIONS ARE SUGGESTED AFTER THE FIRST OCCURRENCE OF TH

                    CONVERGENCE JUDGED UNLIKELY - INCREMENT WILL BE ATTEMPTED AGAIN WITH A SMALLER TIM  INC
                    TIME INCREMENT NEEDED IS LESS THAN THE MINIMUM SPECIFIED - ANALYSIS ENDS
  COMPLETED DURING THIS STEP  0.326     ,  TIME INCREMENT COMPLETED  1.000E-03,  FRACTION OF STEP COMPLETED
  ACCUMULATED TIME              1.33
```

```
... PRODUCTION VERSION 4-7-22                                 DATE  5MAY 90      TIME  0:43:45      PAG:   13
  AT UNIVERSITY OF WINDSOR UNDER ACADEMIC LICENSE FROM HKS, INC.
... 4X4X1/4-65.125" NO RESIDUAL STRESS, TORSIONAL BUCKLING                 STEP    2  INCREMENT
                                                                   TIME COMPLETED IN THIS STEP

                         N O D E   O U T P U T

...ING TABLE IS PRINTED FOR ALL NODES

 ...-     RF1           RF2          RF3          RM1          RM2           RM3
 ...

       6.5176E+04     604.1        32.72        29.31       0.0000E+00    0.0000E+00
       0.0000E+00     604.1        32.72        29.31       0.0000E+00    0.0000E+00

       6.5176E+04     604.1        32.72        29.31       0.0000E+00    0.0000E+00
          23          1023         1023          23            1             1

       0.0000E+00  0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00    0.0000E+00
          1             1            1            1            1             1

 THE ANALYSIS IS ...ED BECAUSE OF THE PROBLEMS ENCOUNTERED
 LOOK AT THE MESSAGES SINCE THE START OF THE LAST INCREMENT FOR THE CAUSE OF THE TERMINATION

                    END OF RUN
```

VITA AUCTORIS

The author was born in 1961 at Chittoor, Andhra Pradesh, India. He completed his higher secondary education with National Merit Honours and graduated with Distinction from Jawaharlal Nehru Technological University (Kakinada Campus), Hyderabad, India in 1983. He obtained his M.Tech. from Indian Institute of Technology, Kanpur in 1985. Thereafter, he joined India's premier consulting engineering organisation, Tata Consulting Engineers at Bombay, where he gained valuable experience in the design of structures and development of related software. He was the author of three major software packages and manuals published and distributed by Tata Consulting Engineers and was author/co-author of two papers on analysis and design of nuclear power plants.

In 1989, he joined the University of Windsor, Ontario, Canada in pursuit of further studies.